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Life cycle analysis of electric and hydrogen buses to improve decision making.

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Abstract:

Pollution and climate change issues are boosting unprecedented impacts on the environment. However, it is also producing an increase of disruptive technological solutions. Regarding public transportation, the trends are heading to the need to limit the negative externalities generated by the service. Consequently, the introduction of electric and hydrogen buses within the regular fleets of transit agencies has had a relevant impact. However, this type of vehicles has other relevant impact to take into account, and to determine properly the impact a long-term perspective is required (not only the use-phase perspective) and the economical perspective is not only considered.

For that reason, the present study proceeds a Life Cycle Assessment of two bus models, an electrical and hydrogen buses. The models are the Volvo 7900 Series, for the electrical option, and the CaetanoBus H2 City Gold, for the hydrogen bus. Therefore, it is seeking a holistically perspective of all the potential environmental impacts related to the manufacture, use-phase (which includes the fuel cycle and the vehicle cycle) and the end-of-life phases. The ReCiPe 2008 methodology is used to categorise and measures the potential environmental impacts. Furthermore, a competitive analysis is also conducted in order to determine the relevant aspects to be changed to enhance the most unfavourable bus model option.

Resumen:

Los problemas de contaminación y cambio climático están impulsando un impacto sin precedentes en el medio ambiente. Sin embargo, también está produciendo un aumento de las soluciones tecnológicas disruptivas. En cuanto al transporte público, las tendencias se dirigen a la necesidad de limitar las externalidades negativas generadas por el servicio. En consecuencia, la introducción de autobuses eléctricos y de hidrógeno dentro de las flotas regulares de las agencias de transporte ha tenido un impacto relevante. Sin embargo, este tipo de veh´culos tiene otros impactos relevantes a tener en cuenta, y para determinar adecuadamente el impacto se requiere una perspectiva a largo plazo (no sólo la perspectiva de la fase de uso) y no sólo se considera la perspectiva económica.

Por ello, en el presente estudio se procede a la evaluación del ciclo de vida de dos modelos de autobús, uno eléctrico y otro de hidrógeno. Los modelos son el Volvo Serie 7900, para la opción eléctrica, y el CaetanoBus H2 City Gold, para el autobús de hidrógeno. Por lo tanto, se busca una perspectiva hol´stica de todos los impactos ambientales potenciales relacionados con la fabricación, la fase de uso (que incluye el ciclo del combustible y el ciclo del veh´culo) y las fases de fin de vida. La metodolog´a ReCiPe 2008 se utiliza para clasificar y medir los posibles impactos ambientales. Además, también se realiza un análisis de la competencia para determinar los aspectos relevantes que deben cambiarse para mejorar la opción del modelo de autobús más desfavorable.

Resum:

Els problemes de contaminació i canvi climatic estan impulsant un impacte sense precedents en el medi ambient. No obstant aixo, també esta produint un augment de les solucions tecnologiques disruptives. Quant al transport públic, les tendencies es dirigeixen a la necessitat de limitar les externalitats negatives generades pel servei. En consequencia, la introducció d'autobusos electrics i d'hidrogen dins de les flotes regulars de les agencies de transport ha tingut un impacte rellevant. No obstant aixo, aquest tipus de vehicles té altres impactes rellevants a tenir en compte, i per a determinar adequadament l'impacte es requereix una perspectiva a llarg termini (no sols la perspectiva de la fase d'ús) i no sols es considera la perspectiva economica.

Per aixo, en el present estudi es procedeix a l'avaluació del cicle de vida de dos models d'autobús, un electric i un altre d'hidrogen. Els models són el Volvo Serie 7900, per a l'opció electrica, i el CaetanoBus H2 City Gold, per a l'autobús d'hidrogen. Per tant, es busca una perspectiva hol´stica de tots els impactes ambientals potencials relacionats amb la fabricació, la fase d'ús (que inclou el cicle del combustible i el cicle del vehicle) i les fases de fi de vida. La metodologia ReCiPe 2008 s'utilitza per a classificar i mesurar els possibles impactes ambientals. A més, també es realitza una analisi de la competencia per a determinar els aspectes rellevants que han de canviar-se per a millorar l'opció del model d'autobús més desfavorable.

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To all my RP friends, my home and family. Always in debt with all of you. I cannot wait to see what life bring us. An important chapter is closing but a new astonishing one is opening just in front of us.

I. Index

II. Figure index

III. Table index

IV. Acronyms and Abbreviations

	Acronyms and Abbreviations
AEB	all-electrical bus
AEC	Alkaline electrolysers
BoP	Balance of plant
CCUS	Carbon capture, utilisation and
CEM	Compressor expander module
EV	Electric vehicle
FCB	Fuel cell bus
FCH	Fuel Cells and Hydrogen Joint Undertaking
FCS	Fuel cell stack
FCV	Fuel cell vehicle
FE	Fuel cell
FFDP	Fossil fuel depletion potential
GDL	gas diffusion layers
GREET	The Greenhouse gases, Regulated Emissions, and Energy use in Technologies Model
GWP	Global warming potential
H2	Hydrogen
HEV	Hybrid electric vehicle
ICEV	Internal combustion engine vehicle
LCA	Life Cycle Assessment
LCI	Life cycle inventory
LCIA	Life Cycle Impact Assessment
LCSA	Life Cycle Sustainability Assessment
MEA	Membrane Electrode Assembly
MPL	Micro-porous layer
NMVOC	Non Methane Volatile Organic Compounds
OFP	Ozone formation potential
PEM	Polymer Electrolyte Membrane
PMFP	Particulate matter formation potential
SOEC	Solid oxide electrolysers
TAP	Terrestrial acidification potential
TCO	Total Cost of Ownership
TMB	Transports Metropolitans de Barcelona
WTP	Well-to- Pump
WTW	Well-to-Wheel

1 Introduction

Life cycle assessment is a powerful tool to improve decision-making. Most of the time, the economical perspective is prioritizing above other options while doing judgments over transportation infrastructures or activities. Part of the impacts therefore are neglected or not taking into account. For that reason, life cycle assessment can provide with relative robustness the life cycle potential environmental impacts related to product systems.

In this case, two models of buses were analysed, both form the economic perspective and environment point of view, more focusing on the latest. Therefore, the present study carries out a Life Cycle Assessment (LCA) and an approximate Total Cost of Ownership (TCO) (as part of the results) of two bus transit models, one electrical and the other hydrogen fuel cell. The LCA analysis is conducted in order to estimate the potential environmental impacts of the two products system related to both bus models during its life cycle (including manufacturing process, fuel production process, use phase and end-of-life phase). The TOC is related to all cost generated while the vehicle is owned (from the related infrastructure cost, maintenance, refuelling cost, among others).

The modelling of the models for the LCA was done by using Greet software, as it was a free and significantly complete tool to conduct LCA. The software was developed by Argonne national laboratory and is an analytical tool that simulates energy use and emission of vehicle and fuel combinations.

By gathering all these information, the aim of the study is to help decisions markers to choose the better option to achieve the decarbonisation of the public transport mobility. The study considers both electric and hydrogen buses as applicable alternatives to accomplish sustainable mobility. The environmental perspective plays a significant role in the election process. Therefore, the LCA provides an approximation of the impacts that are crucial and decisive to enhance the decision procedures. Aspects as the fuel production processes and they related emissions contribution have a relevant role to tipping the scales to one option to another. Complementing this, the economic perspective and the competitive analyses proceeded in this study will enforce and improve the selection of the better option. The relevance of the prices of each fuel used and the investment required to implement and develop the specific infrastructures related to the fuel technologies may vary the competitiveness of each model.

2 Life cycle assessment

Life cycle assessment (LCA) is -as its name states- an environmental analysis, which take a whole life perspective. Its evaluating process not only considers the operative stage impact of any product (the conventional analysis), but adding former stages (i.e. industrial and agricultural processes, such as the extraction of raw materials, the transportation of its material, etc.) and latter stages (i.e. recycling or eliminating material processes) (Hauschild , et al., 2018).

In this chapter, a brief history explanation will be made to understand the evolution of the methodology throughout time. Followed by a review of the main characteristics of Life Cycle Assessments, given an overview on how to proceed with the analysis and the main characteristics it has. In addition, this will lead to an understanding of the strength and possibilities LCA possess and will set the bases of the analysis this work is focused on.

2.1 History brief

During the 1960s decade the educational and industry spheres started to be concerned about environment and the potential negative impacts the human activity can produce over the planet. They began to develop new methods to evaluate these in the USA and in Northern Europe, and were known as Resource and Environmental Profile Analysis (REPA) (Hunt, et al., 1992) or Ecobalances (Hauschild , et al., 2018). Until the early 1990s, the term LCA were not commonly used as the norm.

These initial methods were inspired on material flow accounting by considering inventorying energy and resource use (i.e. crude oil, steel, etc.), emissions and generation of solid waste, from each industrial process in the life cycle of product systems. Due to the increase of inventories complexity, the physical flows of a product and its inventory results started the transition to environmental impact potential results (Hauschild , et al., 2018). This was represent a number of impacts categories (i.e. climate change, eutrophication and resource scarcity) which were contributed by a set of indicators scores for an specific product calculated based on a list of resource uses and emissions (Ali Ibrahim Menoufi , et al., 2011).

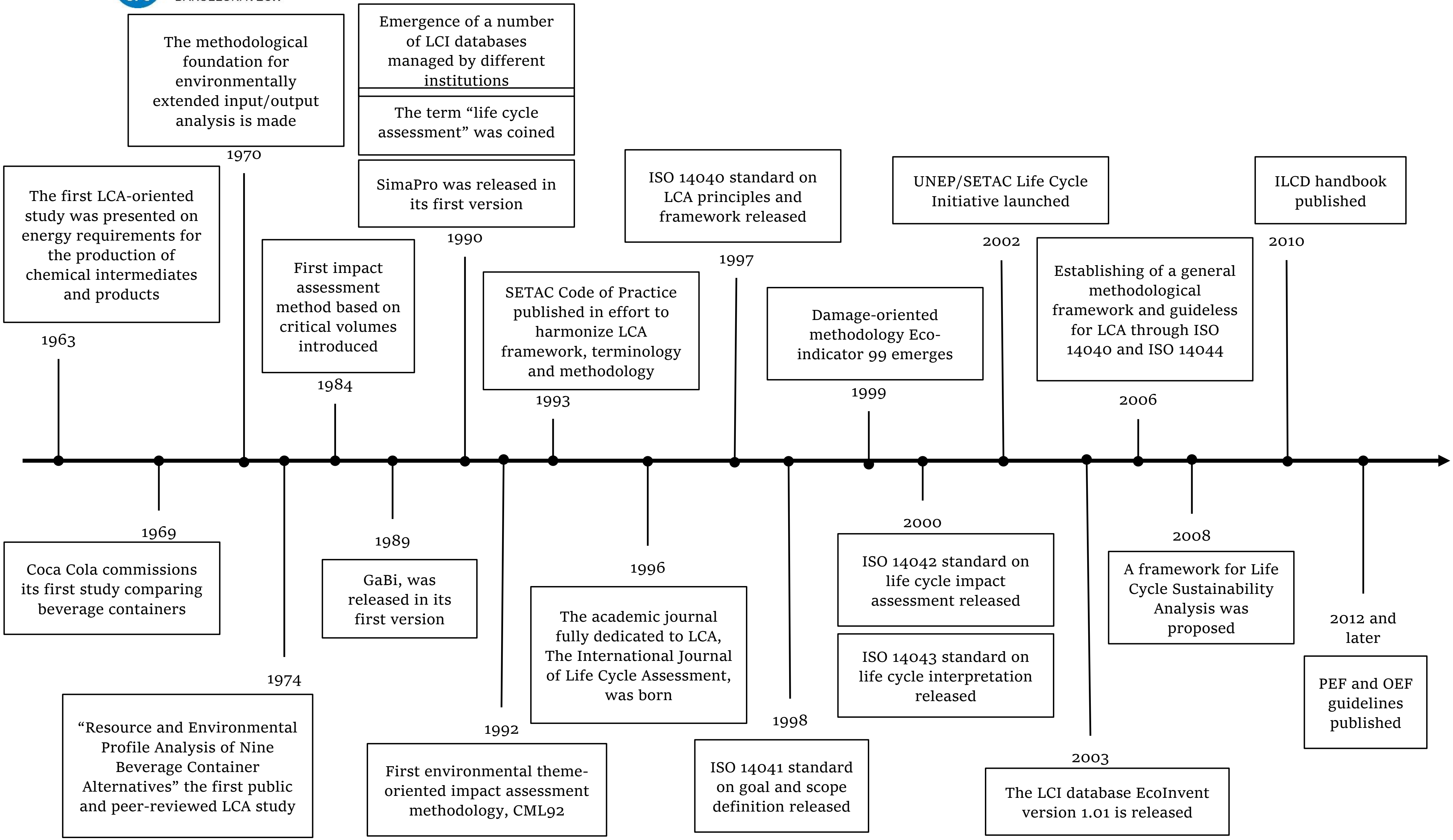
The former methods, however, also varies depending on the public concerns, producing no consistency or harmonisation of the procedure to be flowed (Hauschild , et al., 2018). For example, sometimes the analysis was more focused on generation of solid waste, as the landfilling was the dominant waste management. In other cases, some of the studies were focused only on energy uses as the price of oil were fluctuating.

The goal of avoiding burden shifting become the main objective of impact assessment during the 1990s, hence evading analysing only the public environment concerns. Therefore, the first impact assessment methodology addressed to similar impact categories- as today LCA analysis- was CML92 (Heijungs, et al., 1992) realised by the Institute of Environmental Sciences, Leiden University, Netherlands. After this milestone, other studies were published following similar perspective. For example, The Swedish EPS method, which focused not in midpoints but on damages produced over ecosystems and human health (Steen, 1999); or the Dutch Eco-indicator 99 methodology, which followed a similar approach than The Swedish EPS Method but was improved to enhance the damage modelling (realised on 1999 (Goedkoop & Spriensma, 1999)).

During the same period, diverse organisations and institutes started to generate a variety of inventory databases to help the elaboration of life cycle assessments. However, these databases and data sets were non standardized and the quality of them were low producing differences in assessing the same products systems as resource uses and emissions of industrial processes were no similar. Thankfully, these issues were practically solved due to the publication of the very first EcoInvent database in 2003. This database covered all industrial sectors and origin a consistent data by ensuring standardization and the maximum quality of the data used (Hauschild , et al., 2018).

Simultaneously, over the 1970s, related to the work made by the economist Wassily Leontief on input-output analysis of economies a *top-down"* approach was developed (Leontief, 1970) (Hauschild , et al., 2018). The aim of this work was to generate an inventory produced by the combination of: *national statistics of the trade between sectors with information on sector-specific environmental loads to arrive at an environmentally extended input/output analysis"* (Hauschild , et al., 2018).

The complexity was increasing significantly as the modelling of product systems were getting more multifaceted and the database increased its volume. Therefore, the need for specialised LCA software started to grow and –by 1990- the first versions of SimaPro and Gabi were released (Hauschild , et al., 2018).



1963
The first LCA-oriented study was presented on energy requirements for the production of chemical intermediates and products

1969
Coca Cola commissions its first study comparing beverage containers

1970
The methodological foundation for environmentally extended input/output analysis is made

1974
“Resource and Environmental Profile Analysis of Nine Beverage Container Alternatives” the first public and peer-reviewed LCA study

1984
First impact assessment method based on critical volumes introduced

1989
GaBi, was released in its first version

1990
Emergence of a number of LCI databases managed by different institutions

The term “life cycle assessment” was coined

SimaPro was released in its first version

1992
First environmental theme-oriented impact assessment methodology, CML92

1993
SETAC Code of Practice published in effort to harmonize LCA framework, terminology and methodology

1996
The academic journal fully dedicated to LCA, The International Journal of Life Cycle Assessment, was born

1997
ISO 14040 standard on LCA principles and framework released

1998
ISO 14041 standard on goal and scope definition released

1999
Damage-oriented methodology Eco-indicator 99 emerges

2000
ISO 14042 standard on life cycle impact assessment released

ISO 14043 standard on life cycle interpretation released

2002
UNEP/SETAC Life Cycle Initiative launched

2003
The LCI database EcoInvent version 1.01 is released

2006
Establishing of a general methodological framework and guideless for LCA through ISO 14040 and ISO 14044

2008
A framework for Life Cycle Sustainability Analysis was proposed

2010
ILCD handbook published

2012 and later
PEF and OEF guidelines published

Figure 1. Selected events in LCA history (Source: own elaboration based on (Hauschild , et al., 2018) information).

With the beginning of the millennium and onwards (2000s) the methodology kept continuously been enhanced and updated with new means and studies. With the evolution of this and the comprehension of the differences in the environmental hazards of the individual emissions and the disparity in the sensitivity of the environment absorbing the negative impacts, the EDIP2003 was realised in 2003 (Haischild & Potting, 2005) (Hauschild , et al., 2018). This methodology focused on the differentiation of spatial impact assessment methods, which covered non-global impacts such as acidification and eutrophication.

During the first decade of the 20220s methods for impact assessment of impacts due to extraction-related activities like water use and land use (and regarding to the globalisation of production and a significant increased focus on biobased products) have had a proliferation of studies related and interest (Hauschild , et al., 2018). Because of accounting environmental, social and economic impacts of sustainability a new framework has been developed, called Life Cycle Sustainability Assessment (LCSA). Being the latest efforts on LCA have been focused on the social aspects of sustainability and to quantify social impacts of product life cycles. As a summary, Figure 1 expose selected number milestones of the history and evolution of Life Cycle Assessment methodology.

2.2 Main characteristics

Following the ISO14044, the Life cycle Assessment is defined as a *compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle i.e. from raw material acquisition, via production and use stages, to waste management"* (International Standard Organisation, 2006).

The relevance starts when focus on all the processes a fabricated object goes throughout its life cycle. The extraction of resources is the first stage, followed by production and source transportations and treatment, the operational and maintenance phase and dismantlement and waste treatment or recycling and reuse phases. Actually, life cycle analysis can be done –not only for manufactured objects or product systems- but also for more complex elements, such as companies, energy or waste systems, infrastructure and cities and, the one this work is attached, transport systems (Hauschild , et al., 2018).

By analysing the entire cycle of a product, it permit policy and decision makers to understand the impact throughout time and to identify and prevent aspects that increase and boost the environmental impacts in a single processes or in –eventually- all the life cycle (Hauschild , et al., 2018). In order to mitigate them or eliminate the potential harms a process can bring to the product (i.e. a bus vehicle) itself, making it more sustainable and neutral regarding global warming and other environmental issues.

At the same time, LCA is not only focusing in the most know environmental issue, but to a wide range of different environmental issues. These includes, form the most common climate change issue, to freshwater use problems, land occupations and transformation, aquatic eutrophication, toxic and harmful impacts on human health and fauna welfare, depletion of non-renewable resources and eco-toxic effects from harmful materials and synthetic organic materials (Hauschild , et al., 2018).

Consider life cycle perspective of many environmental issues is in order to avoid and to identify burden shifting. If efforts to mitigate one aspect of the environment issues improve another, it will be a burden shift and the original reason for considering a mitigation action will have no reason to invest in it.

As for commented in many studies, the LCA analysis has a quantitative nature answering the question of *how much does a product system potentially impact the environment?"* (Hauschild , et al., 2018). With this characteristic, LCA is able to compare environmental impacts of different manufacturing process and product systems. A clear example –and the aim of this study- is the life cycle of a hydrogen bus and the comparison with an electric bus to understand which is environmentally better and which contributes better the most to the overall impact and should be prioritise.

To proceed with the analysis, the LCA outcomes requires to calculate and mapping all emissions and sources used in the product process and its geographical locations of theses and use factors and KPIs of the impacts produced by the emissions and resources uses calculated by mathematical models (i.e. the energy mix of Spain is not the same as the USA's, so the environmental impacts of the products produced in each country will be different). A. Bjorn, M. Owsianiak, C. Molin and A. Laurent commented on this the following (2018):

- Firstly, the Life cycle inventory (LCI), the analysis involves thousands of emissions and resource uses. Which is actually the most complex stage of the analysis, *e.g. 0.187 kg CO2, 0.897 kg nitrogen to freshwater, 0.000000859 kg dioxin to air, 1.54 kg bauxite, 0.331 m3 freshwater…"* (Bjørn, et al., 2018).
- Secondly, it is required to classify all the flows into a friendly and controllable number of environmental impacts (some of the most important impacts are stated in the ISO 14040, which is going to be evaluated in next chapters). Which is often yielded to the best estimation" (this means that the parameters associated to the model are consistently chosen) (Bjørn, et al., 2018).

The best estimate" principle followed by the LCA analysis (Hauschild , et al., 2018) go along the capability to proceed comparisons due to the same level of precaution applied in the impact assessment. Nevertheless, best principle" has limitations, associated to the average performances of the processes used in assessing impacts. Which restrain LCA capabilities to add some risky events –no likely but eventually very harmful- such as accidents in industrial sites (Hauschild , et al., 2018).

By quantifying the potential impacts with measurements (i.e. particle counters in urban areas), the LCA ensures robustness and effectiveness in its predictions. Proven casualties (i.e. *the chemical reaction schemes involving nitrogen oxides and volatile organic compounds in the formation of atmospheric ground level ozone"* (2018)) or empirically observed relationships (i.e. *between the concentration of phosphorous in a lake and the observed numbers of species and their populations*" (2018)) are the base for the models of the correlation between emission and impact (Bjørn, et al., 2018).

Inevitably –at the same time- this type of analysis are required to be treated with value judgement (Hauschild , et al., 2018). Mainly while the weighting of environmental issues to assess the impact of a product system. LCA analysis has to maintain a proper value judgment to ensure consistency and transparency. However, simultaneously, LCA value judgment permits decisions makers to decide aspects based on their own experience and knowledge and depending on the countries objectives and policy. In order, for example, to evaluate the environmental impacts of a new transport infrastructure in a certain time period in the future (i.e. 30 years' period).

However, having whole life cycle perspective enlarge its strength as it evaluates impacts from early stages to finally stages covering a large variety of environmental impacts (not avoiding its limitations). At the end, these can be made by gathering thousands of manufacture processes related to thousands more of resources sues and emissions which occurred in different places and happened in different times (Hauschild , et al., 2018). Nonetheless, this main strength also requires simplifications and generalisations that limits LCA from calculating factual environmental impacts regarding to product systems (Bjørn, et al., 2018).

In fact, as many other authors coincide (Hauschild , et al., 2018 and Ali Ibrahim Menoufi , et al., 2011), LCA is more capable to estimate the potential environmental impactes rather than specficic milimetrical impact related to product systems. This is mainly due to unceranties linked to mapping of reources and emissions and the aggregation of calcutaed impacts over time (Hauschild , et al., 2018). Furthermore, the incapability to state if a soltion or producit systems is good enough from the environmental perspective is another limitation for LCA anaylsis. Therfore, results with regard to environmental sustainibility obtained applying LCA analysis can not be taken as absolute or unique solutions and terms.

3 Methodological approach

As commented before, the LCA is carried out to estimate the potential environmental impacts related to two bus transit models of 12 metres long. The first one is the hydrogen fuel cell bus (FCB) CaetanoBus H2 City Gold. The other model compared in the study is the all-electrical bus (AEB) Volvo 7900 Series.

The LCA is conducted to evaluate and estimate the in-puts and out-puts related to the environmental impacts that a product system (i.e. the bus models) generates during its whole life cycle (Simonen, 2014). It includes all phases throughout the life of the vehicle, which includes the manufacture phase, the use phase (which includes the Well to pump phase of the fuel used and the maintenance process) and the end-of-life (which includes the disposal and the recycling process of the vehicle parts) (Muralikrishna & Manickam, 2017). By analyse all the environmental impacts related to each vehicle, LCA allows the decision making to compere qualitatively results with other vehicles/technologies in order to improve and substantiate the decision made (which has to be related to the objectives wanted to achieve regarding suitable mobility). Besides, it will help to understand the impact of the different stages throughout the lifespan of the vehicle and emphasise, for example, the importation of the upstream production process of the fuel used. In other words, not only focus on the potential emissions generated during the driving cycle but to estimate the emissions generated when producing the fuel used as well. In addition, the LCA can be used in more processes and projects with different intentions.

Principally, the LCA can be based on four phases: *goal and scope definition”, inventory analysis”, impact assessment”* and *interpretation of results or conclusions”* (Muralikrishna & Manickam, 2017). Each of the assessment stages influences each other, as it performs in an iterative process (Santesteban Garbe, 2020). Therefore, the methodological approach explained in next chapters are followed in the present study and are based on the guidelines stablished by the ISO 14040/44 (International Standard Organisation, 2006), *Hitch Hiker's Guide to LCA”* (Baumann & Tillman, 2006), and *Life Cycle*

Assessment of PEM fuel cell vehicles and Modelling of Potential Environmental Impacts of PEM Fuel Cell Vehicles" thesis (Santesteban Garbe, 2020).

3.1 Goal and scope definition

The first phase defines the goal and scope of the study (Muralikrishna & Manickam, 2017). It usually tries to define it by formulating different questions like *How do the environmental impacts of city buses depend on their degree of electrification? How do the environmental impacts of electrically chargeable city buses depend on the production of the electricity used for charging?" How do the environmental impacts of electrical operation compare with combustion of HVO instead of diesel?"* (Nordelof, et al., 2014). It defines the context and the basis both for the study structure and scope of analysis by defining also the boundaries of the study (Muralikrishna & Manickam, 2017).

In the case of the present study is to estimate and analyse the potential environmental impacts associated to life cycle of CaetanoBus H2 City Gold fuel cell bus (FCB) and the all-electrical bus (AEB) Volvo 7900 Series. In addition, during the process, the main aspects affecting the environmental impacts should be determined as well in order to evaluate the possible alternative to improve the overall performance or attractiveness of the most disadvantaged.

Therefore, the question to be answered must be, at least:

1. How are compared the life cycle potential environmental impacts related to the CaetanoBus H2 City Gold fuel cell bus (FCB) and the all-electrical bus (AEB) Volvo 7900 Series.
2. How do the environmental impacts of electrically and hydrogen buses depend on the production of the fuel used"?
3. How does the cost of ownership of fuel cell bus compare with the cost of ownership of all-electrical bus?
4. Do the hydrogen fuel cell vehicles represent a real alternative to electrical vehicles to public transport operators?

5. What aspects can be modifying to improve the overall performance of the most disadvantaged vehicle?

The present study aims to contribute to the state of the art and the evaluation of the hydrogen technology as a relevant alternative of suitable mobility. The interest of this technology is growing up so it is relevant to be addressed to the improvement of the technology. Besides, as part of a master thesis conducted in the UPC, the study tries to follow the context and the reality of Barcelona's biggest transport public operator, Transports Metropolitans de Barcelona (TMB). Therefore, phases such as shipment of components, electricity and hydrogen production and energy cost are based on Spain's situation.

Functional unit and system boundaries must be defined as well a part of the first stage of the study (Muralikrishna & Manickam, 2017). The former is used to express all the results obtained in same terms to be able to compare them easily (Baumann & Tillman, 2006). In this specific case, the functional unit used to analyse the results is 100 km driven over the lifespan of the vehicle (which will be addressed in next chapters as 800.000 km). The latest seek to define the system boundary that defines the activities analysed as part of the product system and its related geographical and temporal boundaries of the study (Muralikrishna & Manickam, 2017).

System boundary is related to the lifespan of the vehicle, as it has to consider the different stages included in the life cycle of the vehicle and so does the system boundary. The system boundary is mainly divided and conformed in two sub-cycles (Santesteban Garbe, 2020): the fuel-cycle and the vehicle-cycle. The fuel-cycle encompasses all the processes related to the production and distribution of the fuel used to propel the vehicle from a well to wheel perspective (Baumann & Tillman, 2006). The vehicle-cycle follows the same philosophy and includes all the stages of the vehicle lifecycle in a cradle to grave perspective (i.e. from manufacturing process to disposal and recycling of materials and components) (Baumann & Tillman, 2006). In this case, three main stages are considered, manufacturing phase, using phase and end-of-life phase.

As is commonly done, the system is divided in two systems, the foreground and the background system. The former considers the process that are directly related to the product system (the phases commented before). The latest includes all indirect process related to the product system, which includes material extraction or waste disposal (Santesteban Garbe, 2020). In the following figure can be observed the system boundary related to the present study:

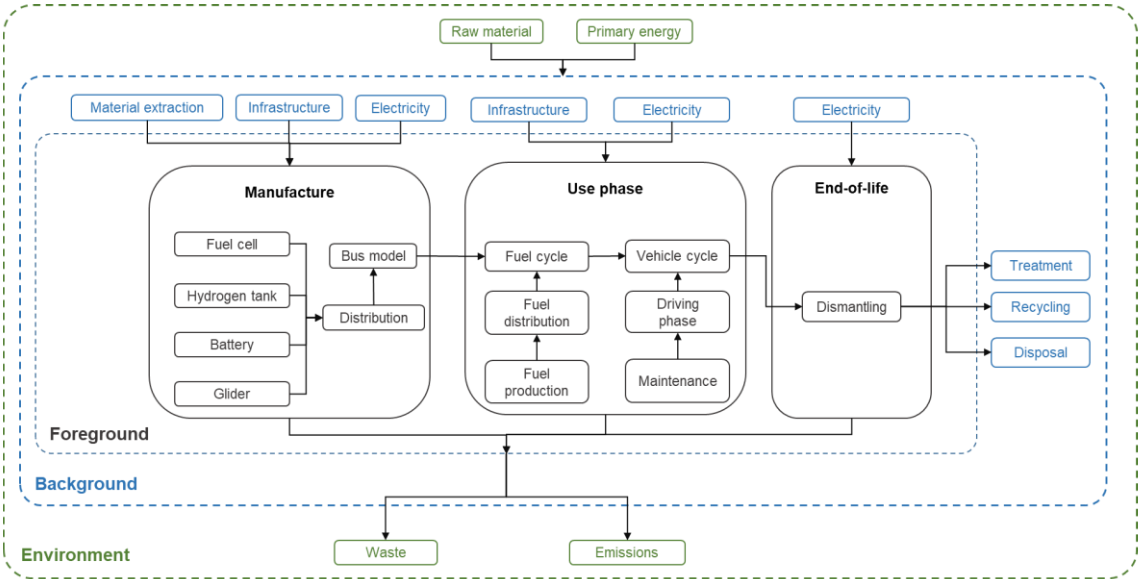


Figure 2. System boundary (Source: own elaboration).

Besides, the assessment must be defined as well to proceed with the study (Muralikrishna & Manickam, 2017). In the present study, it is assessed two different bus models: CaetanoBus H2 City Gold fuel cell bus (FCB) and the all-electrical bus (AEB) Volvo 7900 Series. These vehicles were chosen to match the models used by TMB, Barcelona. CaetanoBus hydrogen bus is currently in operations in the X1 line. However, data and information of the electric bus models operating in TMB lines were no completed and it was not sufficient to proceed properly with the study. Therefore, the Volvo model were chosen as the electric option for TMB (Nordelof, et al., 2019). Some characteristic of both models can be found in the following tables:

Characteristics	**Unit**
Length	12 meters

Permitted GVW	19.500 kg
Passengers	95 pax
Output power	200 kW
Driving range	250 km
Consumption	140 kWh/100km
Batteries system	330 kWh lithium-ion battery pack

Table 1. Volvo 7900 Series main characteristics (Source: (Volvo, 2019)).

Characteristics	Unit
Length	12 meters
Passengers	87 pax
Output power	180 kW
Fuel Cell system	60 kW
Driving range	400 km
Consumption	6 kg H2/100km
Batteries system	44 kWh lithium-titanate oxide batteries

Table 2. CaetanoBus H2 City Gold main characteristics (Source: (CaetanoBus, 2019)).

Fuel cell

Most fuel cells are actually a sum of individual cells, which are called fuel cells (Nordelof, et al., 2014). Each of these cells consists of two electrodes, anode and cathode containing some platinum content as a catalyst, separated by a solid or liquid electrolyte (HyFLEET: CUTE, 2010).

In fact, the fuel cell is composed by the following components (Fan, et al., 2021):

1. Anode: which is responsible to produce the oxidation reaction and to conduct the electrons by being negative charged.
2. Cathode: which is the responsible to produce the reduction reaction and also conduct the electron by being positive charged.
3. Electrolyte: which is basically a proton exchange membrane that allows to block the electron and permit the H+ ions to past through.
4. Catalyst: which is a specific material installed to ease the hydrogen and oxygen reaction, normally being made of platinum.
5. Flow plates: which is the component that facilitates the fuel oxidant flows and its storage.

At the negative electrode (anode) the oxidation of the fuel (usually hydrogen, although there are also cells that use methanol or others) takes place and at the positive electrode (cathode) the reduction of the oxygen in the air takes place, according to the following chemical reactions that take place (Escudero-Escribano, 2011):

- Reaction in the anode: $2H_2 \rightarrow 4H + 4e^-$
- Reaction in the cathode: $O_2 + 4H^+ + 4e^- \rightarrow 2\ H_2O$

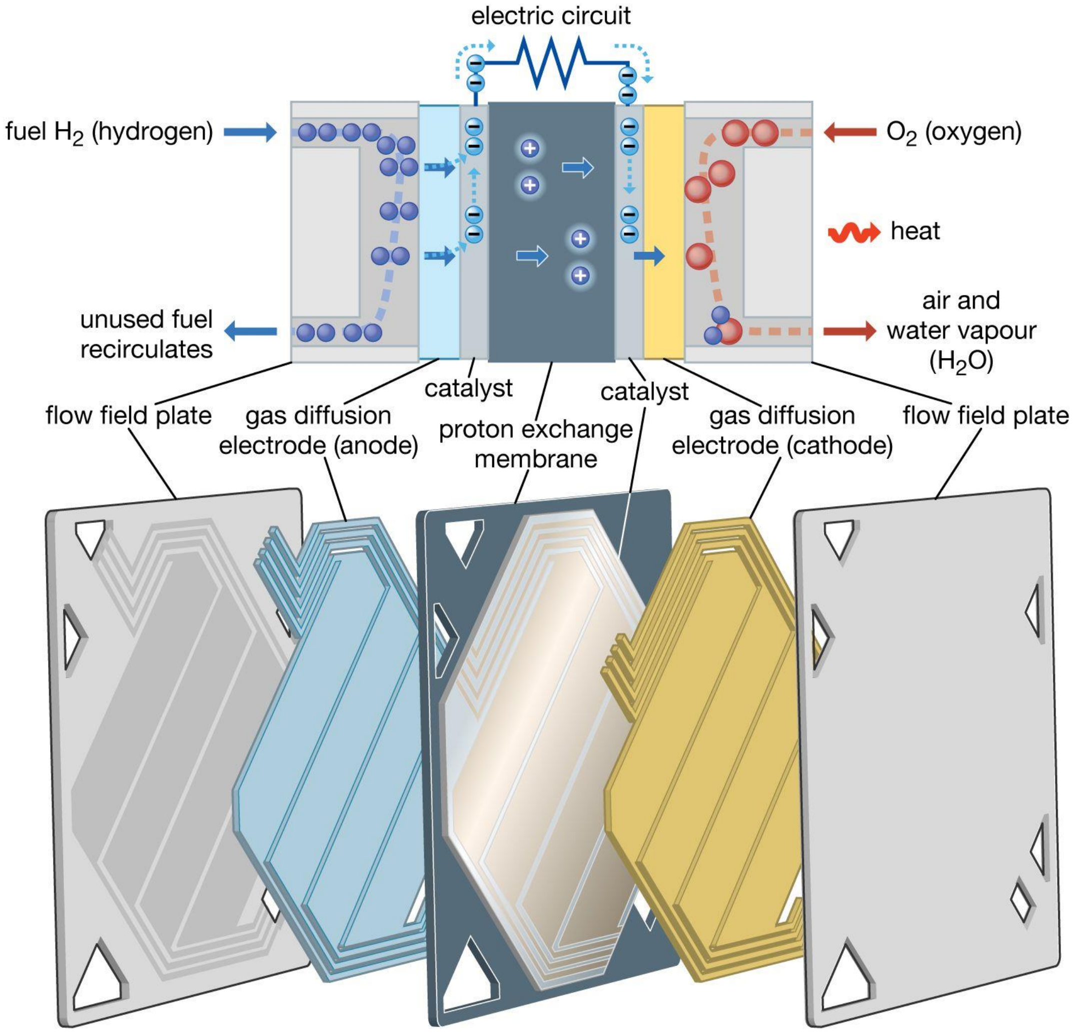


Figure 3. Fuel cell scheme (Source: (Encyclopedia Britannica, 2022)).

The cell of a fuel cell thus consists of an anode into which the fuel (hydrogen) is injected and a cathode into which an oxidant (air or oxygen) is introduced. The two electrodes of a fuel cell are separated by a conductive ionic electrolyte (Carrette, et al., 2001).

Hydrogen enters through the anode and in the presence of a catalyst dissociates into positive ions (protons) and electrons. Oxygen from the air enters at the cathode and dissociates into negative ions in the presence of the catalyst. The hydrogen ions migrate through the electrolyte while the electrons flow through the external circuit. This flow of electrons is the electric current generated by the battery, which is used in electric vehicles to drive the car's electric moto (Carrette, et al., 2001).

Once through the circuit, the electrons reach the cathode, where they combine with the protons and oxygen in the air to form water (Fan, et al., 2021). In other words, they recombine again at the cathode to produce water as the end-product of the reaction, as well as a significant amount of thermal energy (Carrette, et al., 2001).

Generally, the Membrane Electrode Assembly (MEA) is compressed between two plates that act as protection, as well as channelling and distributing the gases in the electrodes, conducting the electrons and facilitating the interconnection in series of the different cells that make up the battery (Carrette, et al., 2001) (Fan, et al., 2021). Thus, the set of cells connected in series by means of these bipolar plates constitute the fuel cell stack, at the ends of which there are two end plates, which act as the electrical terminals of the stack (Fan, et al., 2021).

Although all fuel cells work according to the same basic principle, there are nowadays fuel cells with different designs, operating characteristics and power output. For example, fuel cells can be found on the market with power ratings as low as 1 W operating at room temperature, up to 250 kW modules operating at 1,000 °C temperature. PEM batteries offer the greatest flexibility and versatility for use in the transport sector (Santesteban Garbe, 2020).

3.2 Inventory analysis

Inventory analysis is an important part of the LCA, as it includes the in-puts and out-puts related to the product system (Santesteban Garbe, 2020). The elementary flows given by the functional unit gathered gives as a result the Live Cycle Inventory (LCI) (Santesteban Garbe, 2020).

In order to conform the LCI it is important to define and analysed properly all the actives and phases that the lifespan of the vehicle consist. In this part of the analysis, the flows of the product process must be well defined in order to determine the elementary flows that conforms the product system. In other words, the initial phases that considers resources, materials and intermediated products must be determined and listed according to the corresponding process and in accordance with the reference flow (which defined and related to the functional unit) in order to understand and, again, define the outputs flows. Which are mainly the vehicles manufacturing and other phase’s emissions, the fuel consumption, among others (Santesteban Garbe, 2020).

The Life cycle inventory section considers all these phases and process that consolidates in the final bus models compared and analysed, also considers the energy production as key part in the life cycle assessment carried in the present study.

3.3 Impact assessment

Once the LCI is defined, the results obtained by using the software or any other means must be transformed in a standard scope of environmental impacts assessment. By doing this, the different studies can be compared with the same bases to further enhancement of model robustness. Therefore, this section of the LCA is called the Life Cycle Impact Assessment (LCIA) (Baumann & Tillman, 2006). The LCIA involves the core part of the LCA as the results of the emissions contributed by the system product are addressed in this part.

In the present LCA study, the categories used to assess the product system of both bus models were: Climate change, Terrestrial Acidification, Human health damage due to PM10, Human health damage due to ozone and Fossil fuel depletion. Which were considered relevant environmental impacts related to the vehicles life cycle and were defined by using the ReCiPe 2008 methodology (Goedkoop, et al., 2009). The characterisation methodology follows a hierarchist perspective (Santesteban Garbe, 2020).

To proceed with the LCIA some stapes must be followed in order to standardise the process. The first step it selects the potential impact categories that must be analysed and it principal indicator. Secondly, the classification step must be done. It aims to classify the elementary flows and their contribution to the selected environmental impact category according to the characterisation factor (Baumann & Tillman, 2006). The impacts categories affect three main areas of protection: *Natural Resources”*, *Human Health”* and *Natural Environment*” (Santesteban Garbe, 2020). Consequently, each elementary flow can affect more than one environmental impact category and therefore, more than one area of protection. These can be seen in the following figure:

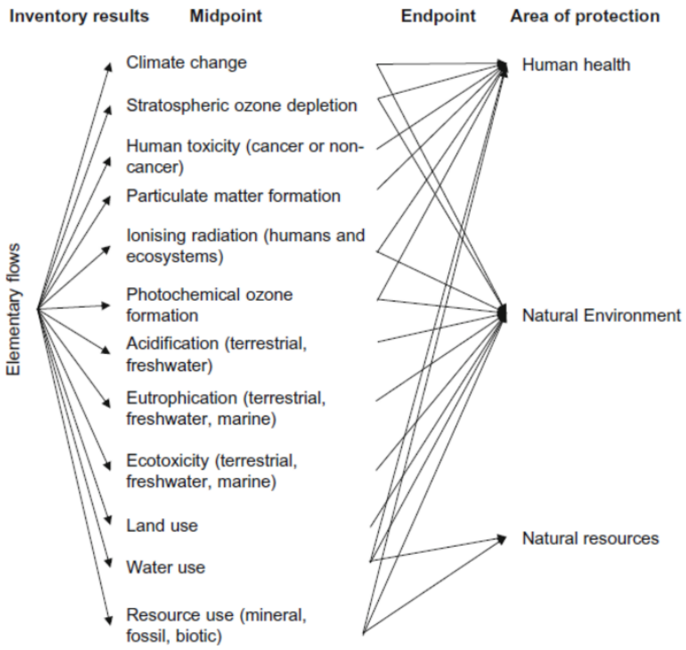


Figure 4. LCIA characterisation (Source: (Simonen, 2014)).

Hence, the characterisation is needed to be done as well. In this part, each of the elementary flows and its environmental impacts are characterized in a unique metric (Santesteban Garbe, 2020). Therefore, an aggregation of all the contribution of each element can be summed and presented as an overall potential environmental impact. This conversion to a same metric is made by the application of a characterisation factor, which is a factor that states the equivalence pollutant contribution of other specific pollutants. These characterisation factors are based on cause-effect chain models (Santesteban Garbe, 2020).

3.4 Interpretation

Finally, the final stage of the LCA is the interpretation of the results (Baumann & Tillman, 2006). In this phase, all the results characterised in previous stages are interpreted and analysed. The results must be used to extract conclusions and recommendations, related to the goal and scope of the study. The main research question presented may be answered by the results obtained. The results have also to be in concordance with the methodological approach, assumption and limitations related to the study (Santesteban Garbe, 2020). In this part, is commonly done a sensitivity and uncertainty analysis in order to validate the conclusions and assumption made during the process (in this specific case, it is conducted more in a performance point of view).

The interpretation is usually made by three steps as Santesteban Garbe comments: *Identify the significant issues from other LCA phases”; Evaluate issues regarding influence on overall results and completeness and consistency with which they have been handled”; Use evaluation results to formulate conclusions and recommendations”* (Santesteban Garbe, 2020).

3.5 Software used

The methodological approach of the LCA can be relative easily to understand. However, take that theory into practice is usually the most complicated process as the complexity; relations between production system and the availability of date set are sometimes really complicated.

For that reason, specialized LCA software are an indispensable tool to proceed this type of analysis. The software develops adapted frameworks to ease the process and the analysis. Normally, they include inventories and data set to be able to calculate the potential impacts. The databases or data sets are key in order to have the specific information about products and process that will allow doing the analysis. This is also one of the main barriers related LCA, as most of the time the most complex dataset requires a purchase process. In this study, some limitations were related to the acquisition of potent and full datasets form EcoInvent (which are the most common database used). The purchase of the dataset was extremely unaffordable.

However, in the study the Greet software and datasets were used, as it was a free and significantly complete tool to conduct LCA (Argonne National Laboratory, 2022). Greet is the acronym for the greenhouse gasses, Regulated Emissions, and Energy use in Technologies. The software was developed by Argonne national laboratory (Argonne

National Laboratory, 2022) and is and analytical tool that simulates energy use and emission of vehicle and fuel combinations. It was used because it is a tool that is especially focused on mobility analysis, has a big datasets of vehicle technologies and processes so it meets the expectations to carry out properly the analysis. In addition, it models development met the phases that must be included in LCA analysis.

Argonne National Laboratory also developed the data used. The characterisation data, emission factors and other relevant information were developed by means of conducting specific LCA. This means that the background data bases that Greet uses is composed by other LCA that takes into account geographical locations, transportation process and different production process, which enhance the robustness of the data and the software itself. For example, they develop a full life cycle assessment of the steel production (also with other relevant materials and components) where the geological location of raw materials was taken into account and they at its result to the software background data. Besides, the information is continually updated and enhanced (Argonne National Laboratory, 2022).

4 Life cycle inventory

As commented in other sections, an important step to proceed with the LCA is to outline all the elementary systems flows or also called Live Cycle Inventory (LCI) by analysing the product system in order to list and determine the associated inputs and outputs. In this case, the structure of the LCI includes three main stages (Nordelof, et al., 2019) (Davide, et al., 2022): manufacture process, use phase and end-of –life stage. This take into account both the vehicle and fuel cycles.

4.1 Fuel cycle

The fuel cycle is characterized from the well-to- pump (WTP) perspective (Santesteban Garbe, 2020). In this study, this process includes the production of the production, the distribution of the hydrogen and the electricity (by also accounting different pathways to produce them) and the refuelling phase (which sum all the impacts generated by consumption of hydrogen during the use phase of the vehicle). It is important to highlight that all base data and information of the pathways of the production of hydrogen and electricity are stablish from the background data of Greet (Argonne National Laboratory, 2022) as commented before.

4.1.1 Electricity mix

As this study is focused on electric transit buses, the generation of the energy to supply these vehicles is relevant. To do this, the base electricity mix given by Greet (Argonne National Laboratory, 2022) was modified to match the characteristics of the Spain electricity network (REE) (Red Eléctrica Corporación, S.A , 2022). In the following figure, it can be seen the share of the different resources involved in the electricity production in Spain:

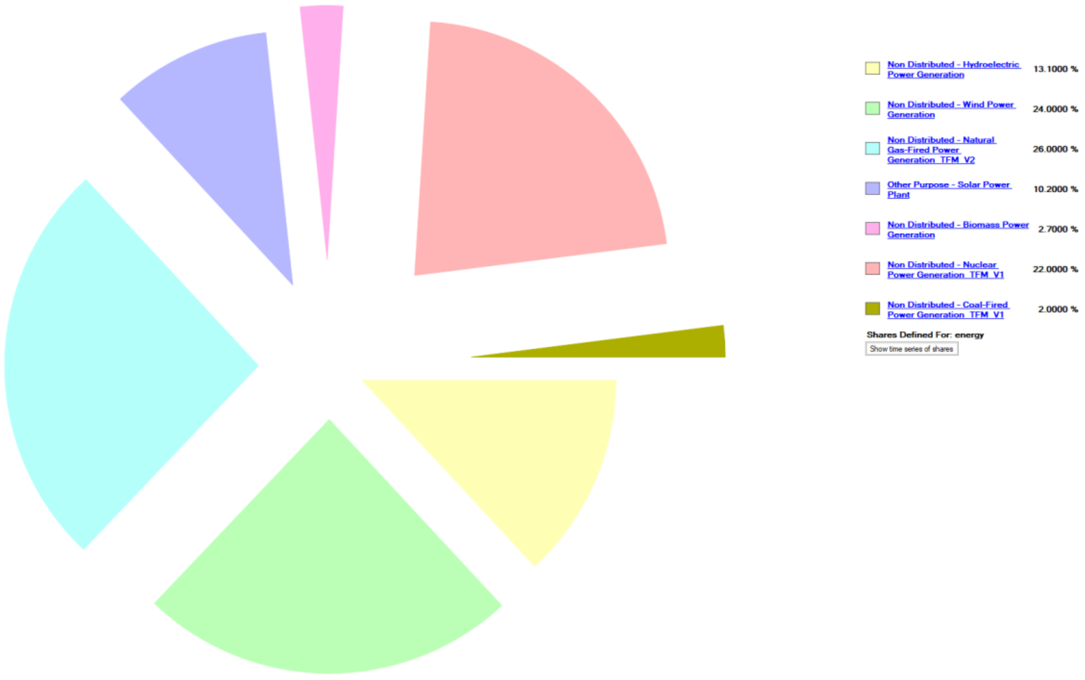


Figure 5. Spain electricity mix (Source: own elaboration using Greet software based on (Red Eléctrica Corporación, S.A , 2022)).

Nonetheless, the background information of Greet (Argonne National Laboratory, 2022) takes into account the processes done and technologies used in USA to produce energy from natural gas, coal, nuclear power, biomass, hydroelectric, wind power and solar power plants, some modifications were made to adjusts such process to the Spain electricity mix.

For example, regarding electricity produced by natural gas the distribution pathway was changed and the resources required to this means. In this case, the transportation of the gas was modified to consider the main importer of this source to the power plants in Spain, which is the natural gas from Algeria (ICEX Espana Exportación e Inversiones, 2022). Gas pipelines, starting in Algeria and arriving to Almeria, make the transportation. The assumed distance of this pipeline added in the model was of 747 km (Engas, 2022). In addition, the distance from Almeria to Catalonia community was also added to the model. This means an addition of 921 km to the transportation process (Engas, 2022).

Same modification was done to the enriched uranium that was assumed to be purchased from Russia (Europa press, 2022). Therefore, the transportation is assumed to be done by two specialized modes (Foro Nuclear, 2021) (Consejo de Seguridad Nuclear, 2022), rail for 3.500 km and by lorry for 120 km until reach the Ascó Nuclear Plant (located in Catalonia) (Ministerio para la Trancisión Ecologica y el Reto Demográfico, 2022).

The other different sources were not modified and were assumed the same as Greet background information (Argonne National Laboratory, 2022).

Finally, regarding distribution process of the electricity produced, it was assumed that the losses of the processes were the same as the European. Which is 6.44% (Kelly, et al., 2020) also assumed by Greet default background data (Argonne National Laboratory, 2022).

4.1.2 Hydrogen production and technologies

4.1.2.1 Hydrogen production

Hydrogen (H) is the simplest and smallest chemical element, consisting of a single proton and an electron (Yue, et al., 2021). Because of its structural simplicity, it is the most abundant element in the universe, present in massive form in stars and gaseous planets. However, it is present as part of other molecules not founded individually in abundance. Therefore, an important aspect related the production is the separation of hydrogen from other molecules (Yue, et al., 2021), which usually requires huge amounts of energy.

Under normal conditions, hydrogen is found as a diatomic gas molecule. It has a high-energy value per unit of mass, much more than traditional fuels (Yue, et al., 2021). In addition, its compression, liquefaction or transformation to other fuels requires additional energy that has to be taken into account in the energy balance, as commented before.

Although the physicochemical properties of hydrogen may not be ideal for its simple, direct and massive incorporation into our economy, the potential benefits it could bring are important enough to consider its significant role in the value chain, if the appropriate safety measures are taken into account (Pareek, et al., 2020). Its main advantages are (Pareek, et al., 2020):

- It only generates water because the combination off oxygen it is used as fuel. It does not produce carbon dioxide
- The reserves are inexhaustible, as it is a renewable fuel.
- It can be physically stored relatively easily, either as a pressurised gas or as a liquid.

These properties are essential to overcome the challenges that exist in order to build an economy based on renewable hydrogen and to develop its application, such as a fuel" for vehicles (i.e. buses, trains, airplanes, etc.).

According to the roadmap of the Ministry of Ecological Transition (Ministerio para la Transición Ecológica y el Reto Demográfico, 2022) and the Spanish Hydrogen Association (Asociación Espanola del Hidrógeno, 2022), three principal types of hydrogen are distinguished according to the type of production:

1. Green hydrogen
2. Blue hydrogen
3. Grey hydrogen

The Figure 6. Selected technology options and feedstocks" (Source:).shows which processes are used according to the resource needed and what type of hydrogen is obtained (Nnabuife, et al., 2022). It is important to highlight that hydrogen form biomass and biocombustibles are considered green. It should be noted that the processes and resources used to obtain blue hydrogen are the same for grey and similar for blue.

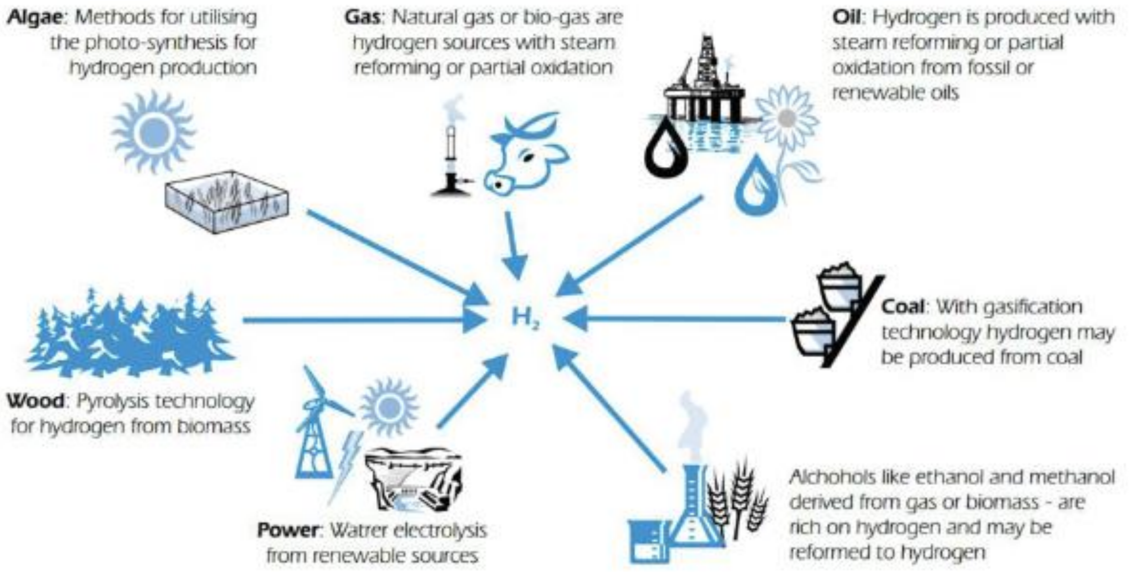


Figure 6. Selected technology options and feedstocks" (Source: (Nnabuife, et al., 2022)).

4.1.2.1.1 Natural gas

One of the processes to obtain hydrogen is from natural gas reforming (or also, called steam methane reforming). The reforming of natural gas (also perhaps from alcohols or waste) is based on the decomposition of the methane molecule to give hydrogen and carbon oxides (CO and CO_2). For this process to take place, a combination of three conditions is required (Office of Energy Efficiency & Renewable Energy, 2020):

- High temperature (700-1100 ° C).
- Presence of a catalyst (nickel base).

- Presence of an oxidising agent (water or air).

The process is divided in two stages. Firstly, the hydrocarbons is mixed with the steam, where exothermic chemical reaction take place to oxidize partially the methane (Office of Energy Efficiency & Renewable Energy, 2020). The result is a gas formed by hydrogen and carbon monoxide. Then the carbon monoxide is oxidized to carbon dioxide and additional water is reduced within a catalytically conversion (Office of Energy Efficiency & Renewable Energy, 2020). Finally, the result is purified to have as much as hydrogen possible.

It is the most common process used to produces hydrogen due to the high availability and low cost of natural gas (Santesteban Garbe, 2020). In Spain it is consumed approximately 500.000 t/year of hydrogen, 99% of the hydrogen produced being grey hydrogen from natural gas (Ministerio para la Trancissión Ecológica y el Reto Demográfico, 2020). It is produced in large-scale plants where massive amounts of methane are reforming, meaning that Economies of scale are achieved. This means that is the cheapest and most efficient production process for the hydrogen nowadays and it produces less GHG emissions compared to other fossil fuel hydrogen-base production (Rodl, et al., 2018).

4.1.2.1.2 Gasification

Gasification is a process that converts organic matter into synthesis gas (CO, CO_2 and H2 mixture) (Nnabuife, et al., 2022). During the process, a partial oxidation of a solid material is performed at a certain temperature to break down its compounds and transfer them to the gas phase, thus facilitating their use as a fuel (synthesis gas) or to obtain compounds separately (hydrogen) (Nnabuife, et al., 2022).

The operating principle of classical gasification is to produce a reaction between long-chain hydrocarbons (i.e. fuel oil, coal, biomass or waste) and oxygen or water (Nnabuife, et al., 2022). The amount of oxygen is always in controlled to avoid complete oxidation to carbon dioxide and water. Oxygen has to be introduced in the purest possible form to increase the hydrogen concentration at the outlet and to avoid the formation of nitrogen compounds (Nnabuife, et al., 2022). The gasification process takes place at high temperature (1200-1400 °C) and, if the oxidation conditions are very low, it becomes more of a pyro-gasification process. These high temperatures are achieved and maintained by the exothermicity of the reaction itself and do not require an external fuel as in the case of reforming. The pressure used in gasification varies depending on the technology. Finally, the yield increases with increasing pressure, but it can take place at atmospheric pressure (Nnabuife, et al., 2022).

4.1.2.1.3 Electrolysis

Electrolysis technology consists of the dissociation of the water molecule into oxygen and hydrogen in a gaseous state by means of a continuous electric current, supplied by a power supply connected to two electrodes, at the surface where the water molecule is broken down (Godula-Jopek, 2015). For the application of this technology, there are several types of electrolysers, among which the following stand out:

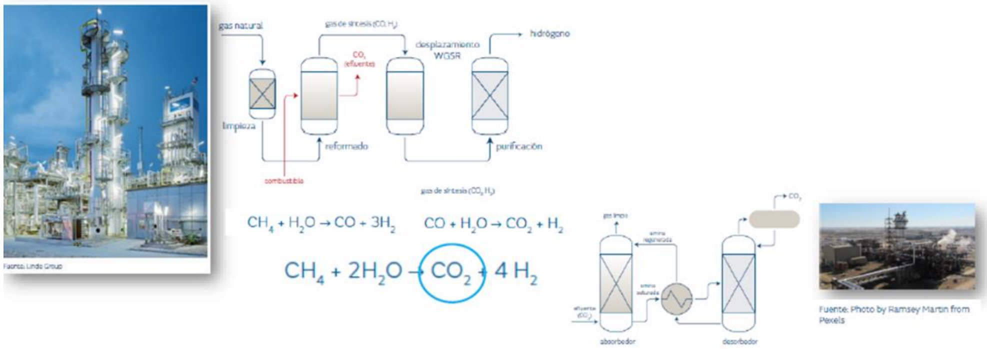
1. Alkaline electrolysers (AEC): The electrolyte where ion conduction takes place is an alkaline solution, generally potassium hydroxide (KOH) (Bhandari, et al., 2014). They are the most common electrolyser, as they are the most economically profitable and technologically mature (Bhandari, et al., 2014). It is a technology with a low electricity density, which implies a lower amount of hydrogen per volume of equipment. Which means that the hydrogen production is limited to an operating range of 20-100% of nominal performance, because the gases generated at the anode and cathode can undergo diffusion through the diaphragm (Bhandari, et al., 2014).
2. Proton Exchange Membrane (PEM) electrolysers: In this case, the electrolyte is a solid proton conducting polymer, reducing the corrosion problems of the previous one in terms of system, which affect the individual components of the electrolyser (Nikolaidis & Poullikkas, 2017). In addition, the use of precious metals is required, which implies higher costs, although they can operate at higher current densities and allow easy coupling to fluctuating systems, such as renewable energies.

3. Solid oxide electrolysers (SOEC): This is the least developed technology. The electrolyte is made with ceramic materials, which allows the reduction in manufacturing costs, and have a high degree of energy efficiency, although it has to work at temperatures above 700 ° C (Anon., 2008). Unlike the previous ones, they allow the hydrogen generated to be converted into electricity again if reversible devices are used, providing balancing services in the grid.

4.1.2.1.4 Blue hydrogen

Hydrogen obtained in a similar way to grey hydrogen, but with the application of carbon capture, utilisation and storage (CCUS) techniques (Carbon Capture, Utilization and Storage), which reduces CO_2 emissions generated during the process by up to 95% (Oni, et al., 2022).

It is the same process as grey hydrogen, but there is a further process, where CO_2 is place in storage facilities. With this carbon dioxide capture process, called pre-combustion, a very significant reduction of greenhouse gas emissions can be achieved, around 60-75% (Oni, et al., 2022).



Fuente: Linde Group

Fuente: Photo by Ramsey Martin from Pexels

Figure 7. Hydrogen and synthesis gas plant, hydrogen production process by reforming and CO_2 capture by absorption technology (Energetica, 2002).

There are several processes for generating blue hydrogen. The main ones are reforming, gasification, cracking and electrolysis (Oni, et al., 2022).

4.1.2.1.5 Green hydrogen

Is the hydrogen generated from renewable electricity, using water as feedstock, by means of an electrolysis process (Kakoulaki, et al., 2021). Likewise, hydrogen obtained by biogas reforming or biochemical conversion of biomass, if the established sustainability requirements are met, are considered green energy.

There are several processes for the generation of green hydrogen. The main ones are electrolysis, reforming and gasification. However, recent efforts are made in order to used green hydrogen produced by electrolysis powered by renewables as key aspect to boost hydrogen use and achieve sustainable objectives (Kakoulaki, et al., 2021).

4.1.2.2 Compressed gaseous hydrogen production

The pathway to produce gaseous hydrogen was modified similarly. As commented before, this fuel can be produced in different manners, such as steam methane reforming (natural gas), water electrolysis and coal gasification.

In the Spain case, the hydrogen consumed is mainly produced by means of natural gas. In fact, in the country it is consumed approximately 500.000 t/year of hydrogen, 99% of the hydrogen produced being grey hydrogen from natural gas (Ministerio para la Trancissión Ecológica y el Reto Demográfico, 2020). Nonetheless, the hydrogen is used in other sectors nor the transport sector, like primarily used in refineries (about the 70%) and in chemical product factories (25%) (Ministerio para la Trancissión Ecológica y el Reto Demográfico, 2020).

In consequence, in order to give the study with relevant information to proceed properly with the analysis, it was assumed that the hydrogen is produced in three different ways (from natural gas and by electrolysis in large-scale plants and by electrolysis directly in the refuelling station).

Therefore, the hydrogen production base scenario is founded in steam methane reforming produced in a specialized large-scale producer plant. Due to the lack of information regarding the compressed gaseous hydrogen production, it is assumed that

Greet background pathways called *Compressed G.H2 Produced from NA NG"* (Argonne National Laboratory, 2022) regarding the fuel production are the same as the Spain pathways. In consequently, the technologies and the main process for the production of the hydrogen were stablish from the background information and data sets of Greet (Argonne National Laboratory, 2022).

As Ministerio para la Trancissión Ecológica y el Reto Demográfico (2020) commented, nowadays a hydrogen pipelines networks does not exist and the investments are significantly big (so no changes in this situation is expected in near future). Hence, the transportation processes can be made by using the actual pipelines network of the gas sector (with the related pros and cons) and by specialized tube trailers. In the specific case of the study presented, the main mode use for the compressed gaseous hydrogen transportation is tube trailers. The vehicles called in Greet *Heavy-duty truck"* uses diesel fuel (Argonne National Laboratory, 2022) and are able to transport 362 kg of compressed gaseous hydrogen (Ministerio para la Trancissión Ecológica y el Reto Demográfico, 2020)).

However, changes in the electricity mix used for compression stages were made (to use the Spain electricity mix). The compression process takes places both in the central plant before the transportation stage (called in Greet *G.H2 Electric Compression tube trailers loading"*) and in the refuelling station in order to storage safely the hydrogen (called in Greet *G.H2 Electric Compression for Refuelling Station"*). Besides, the base Greet pathway includes a transportation process from the natural gas central to the refuelling station typically with enormous range of kilometres driven. Nonetheless, the distances in Spain are considerably smaller so it was assumed that the tube trailer travel 50 km from the hydrogen central plant to the refuelling station.

Regarding electrolysis, two scenarios were created in order to analyse the impact of the different gaseous hydrogen production in the LCA. The former scenario takes into account the Spain electricity mix to accomplish the electrolysis in a large-scale central plant. The technologies for the electrolysis, the sources required and the related emission generated were also modelled by using the Greet background pathways and datasets called *G.H2 Production by Electrolysis from HTGR electricity (H2A Model)"* (Argonne National Laboratory, 2022). Assumptions with respect the transportation (Ministerio para la Trancissión Ecológica y el Reto Demográfico, 2020) (Argonne National Laboratory, 2022) and the compression stages were the same as the compressed gaseous hydrogen produced in a large-scale central plant by using natural gas commented before (Argonne National Laboratory, 2022).

The final scenario made for the study was the production of the compressed gaseous hydrogen directly at the refilling station using removable energy as a principal resource to accomplish the electrolysis. This scenario tries to model the *Hidrogenara de Iberdrola"* located in Zona Franca, Barcelona, which produces only green hydrogen (Iberdrola, 2022). The TMB hydrogen buses uses this hydrogen refuelling station as part of a partnership between Iberdrola and TMB (Iberdrola, 2020) that allows this last one to consolidate its leadership in suitable urban mobility.

To model this scenario, the assumed pathway from Greet used was *Compressed Gaseous Hydrogen from Electrolysis (HTGR)".* This uses electricity as a principal resource, which in this case was a mix made of only renewable energy. Specially, it was assumed that the renewable electricity mix was composed by an equal share of energy from solar power plants, hydroelectric power generation and wind power generation. The equal share was assumed to be like that due the lack of information regarding the exactly electricity used by Iberdrola at the refuelling station. The technologies regarding the three renewable pathway electricity generation, the primary sources required and the related emission generated were also modelled by using the Greet background pathways and datasets called. (Argonne National Laboratory, 2022). In the following figure can be observed the Spain renewable electricity mix:

Figure 8. Spain renewable electricity mix (Source: own elaboration by Greet software).

However, the electricity used to compress the gaseous hydrogen was assumed to be taken from the Spain electricity mix, as the information about this process was not clear (Iberdrola, 2022) and it was relevant to be on the conservative side regarding this scenario.

4.2 Vehicle cycle

Vehicle cycle have to consider all the stages regarding cradle-to-grave perspective. (Garc´a Sánchez, et al., 2013) (Davide, et al., 2022). Which includes the manufacture and use phase and end-of-life (Santesteban Garbe, 2020).

4.2.1 Manufacture phase

As commented before, the present study carries out and LCA to compare the impacts of two different technologies of energy propulsion: all electric bus (AEB) and a fuel cell bus (FCB). Therefore, the manufacture phase includes the extraction and acquisition of raw materials, components production and manufacture and assembly phases.

In this particular case, the comparison is made between the AEB Volvo 7900 Series (Volvo, 2019) and the FCB CaetanoBus H2 City Gold (CaetanoBus, 2019), both of 12 metre long. The reason for select these two models of transit busses as commented before was to compare two vehicles in commercialization and fully operational. Besides, the bus manufactured by CaetanoBus is actually the unique H2 bus in operation in TMB's fleet operating in the X1 line (Transports Metropolitans de Barcelona, 2022). However, the reason to choose Volvo 7900 series bus was due to the available information about its materials and manufacture processes (Nordelof, et al., 2019), missed in other busses used by TMB. Therefore, it will facilitate the medialisation process in Greet.

The basic data and assumptions used during the medialisation of the two different bus models were fundamentally form Nordelof, et al. (2019) regarding Volvo's bus and also de official web page of Volvo (Volvo, 2019) and from Garc´a Sánchez, et al. (2013), which also give some relevant information about the characterisation of electric buses. In regard to fuel cell vehicle, the information were more complicate to found and some assumption of chassis, vehicle body and other parts were needed based on Nordelof, et al. (2019) and Volvo information.

However, concerning the Fuel Cell Stack produced by Toyota, the base information was based Santesteban Garbe (2020) which used information of the Mirai FCV manufactured by Toyota. In addition, data inventories of other authors were used in this study to assess the mater of produce a proper and robust medialisation of the Fuel Cell Stack, such as Miotti et al. (2017), Evangelisti et al. (2017), and Chen et al. (2019).

However, the FCS modelled by these studies were only 56,2 kg, which was the first model of FC produced by Toyota (Toyota, 2018). Nonetheless, the fuel cell used by Caetano buses are the evolution of the first generation. The second generation of the Toyota's fuel cell stack is actually used for both the Toyota Mirai vehicle and the H2 City Gold bus (CaetanoBus, 2019). The second-generation of FCS weight approximately 240 kg (Toyota, 2020). However, no specific information about its components were found. Consequently, it was assumed that the components of the first-generation of Toyota FC were the same as the second-generation but with an applied conversion factor of 4,27 (which was the ratio between the weights of the two FC generation) in order to meet the characteristics of the new generation of fuel cells stacks.

4.2.1.1 Chassis

The chassis was modelled based on the weights information given by Nordelof, et al. (2019) and using the composition of the light chassis model given by Greet (Argonne National Laboratory, 2022) called *MHDV: Combination Long-Haul Truck - Chassis (ICEV, HEV, EV, FCV)"*. It was assumed also that both vehicles possess the same chassis due to the lack of information regarding CaetanoBus chassis components.

The weight of the chassis was assumed therefore to be 5.632 kg (Nordelof, et al., 2019). The components and the related amount for 1 kg of chassis were the following:

Chassis materials	**Greet dataset used**	**Amount per 1 kg**
Steel	Average steel	0,15
Iron	Final Iron product (combined)	0,091
Wrought aluminium	Average wrought aluminium	0,012
Cast aluminium	Average cast aluminium	0,593
Copper wire	Copper wire	0,008
Plastic product	Final average plastic product: combined	0,011
Glass fibber	Glass Fibber Reinforced Plastic Production Mix	0,061
Other vehicle materials	Other vehicle materials	0,007
Rubber	Final Compression Moulded Rubber Product	0,06

Table 3. Chassis materials and amounts per 1 kg of chassis (Source: (Argonne National Laboratory, 2022) (Nordelof, et al., 2019)).

4.2.1.2 Vehicle body

The vehicle body characterisation is similar to the chassis. The weights and some of the components were assumed equal as Nordelof, et al. (2019). The interior equipment and materials are also included in the vehicle body dataset. However, some of the components were not specified in any study. Therefore, the bases vehicle body of Greet called *MHDV: Combination Long-Haul Truck - Vehicle Body (ICEV, HEV, EV, FCV)*" were used (Argonne National Laboratory, 2022).

The weight of the vehicle body was assumed therefore to be 4.115 kg (Nordelof, et al., 2019). The components and the related amount for 1 kg of vehicle body were the following:

Vehicle body materials	Greet dataset used	Amount per 1 kg
Steel	Average Steel	0,281
Stainless steel	Stainless Steel Production	0,021
Wrought aluminium	Average wrought aluminium	0,092
Cast aluminium	Average cast aluminium	0,031
Plastic product	Final average plastic product: combined	0,162
Styrene	Final Average Rubber Product: Combined	0,018
Glass fibber	Glass Fibber Reinforced Plastic Production Mix	0,137
Glass	Flat glass production (For Automotive Use)	0,080
Copper wire	Copper wire	0,003
Damask	Damask Production - Pathway	0,029
Latex	Latex Production - Pathway	0,022
Lather	Leather Production - Pathway	0,015
Graphite	Graphite Production (Battery Materials)	0,001
Silica	Silica Production - Pathway	0,001
Cotton paper	Cotton Paper Production - Pathway	0,0004
Wood	Wood Production - Pathway	0,107

Table 4. Vehicle body materials and amounts per 1 kg of vehicle body (Source: (Argonne National Laboratory, 2022) (Nordelof, et al., 2019)).

4.2.1.3 Battery

The battery has different manners, for an electric bus it storage all the electric of the chargers. However, in the FC bus, the battery is stores the energy produced by the FCS, as well as the recovered energy from the brakes (Santesteban Garbe, 2020).

Although there were no information about the quantity of the batteries used for the Volvo 7900 series, Nordelof, et al. (2019) stated that they were Lithium-ion batteries. Besides, Nordelof, et al. (2019) also commented that the battery pack weight was equal to 1.536 kg. Volvo also stipulate that the capacity of the batteries were a total of 330 kWh (Volvo, 2019).

Regarding to the CaetanoBus H2 City Gold, the only information available was that the batteries used were Lithium-titanium and the capacity of them were between 29 and 44 kWh (CaetanoBus, 2019). Therefore, to proceed to the modelling it was assumed that the CaetanoBus uses lithium-ion batteries (Greet does not have data sets for lithium-titanium batteries). Finally, it was also assumed that –as the requirements of the batteries are smaller compared to the electric bus- the pack of batteries was only conformed of two batteries of 44 kWh and had 285 kg each. These are characteristics of the batteries used by other CaetanoBus model, the eCity Gold, supplied by Forsee Pwer (Forsee Power, 2022).

Consequently, the dataset use to model the lithium-ion batteries for Volvo 7900 series was *MHDV: Combination Long-Haul Truck - Electric - Lithium-Ion Battery - Bill-of-Material – Process"* (Argonne National Laboratory, 2022). The materials and the related amount for 1 kg of battery were the following:

Lithium-ion battery materials	Greet dataset used	Amount per 1 kg
Graphite	Graphite Production (Battery Materials)	0,183
PVDF	PVDF Production (Battery Materials)	0,010
Copper wire	Cotton Paper Production - Pathway	0,161
Wrought aluminium	Average wrought aluminium	0,191

Lithium-ion battery materials	Greet dataset used	Amount per 1 kg
Lipf6	LiPF6 Production (Battery Materials)	0,014
Ethylene carbonate	Ethylene Carbonate Production (Battery Materials)	0,039
Dimethyl carbonate	Dimethyl Carbonate Production (Battery Materials)	0,039
Polypropylene	Final PP Product: Combined	0,014
High-density polyethylene	Final HDPE Product: Combined	0,004
Polyethylene terephthalate	Final PET Product: Combined	0,002
Steel	Steel Production from FIT100%H2 EAF Mix	0,001
Glass fibber	Glass Fibber Production	0,005
Power train coolant	Engine/Powertrain coolant from ethylene glycol	0,023
Battery management system	Battery Management System Production (Battery Materials)	0,001
NMC 622	Production of NMC(622)	0,312
n-menthyk-2-pyrrolidone	N-Methyl-2-pyrrolidone Production (Battery Materials)	0,002

Table 5. Lithium-ion battery for the Volvo 7900 series materials and amounts per 1 kg of battery (Source: (Argonne National Laboratory, 2022)).

For the batteries used for the FC bus, the materials were the same than the ones used for the electric bus, only some changes in the amount of materials for 1kg of battery were made (Argonne National Laboratory, 2022):

Lithium-ion battery materials	Greet dataset used	Amount per 1 kg
Graphite	Graphite Production (Battery Materials)	0,089
PVDF	PVDF Production (Battery Materials)	0,005

Lithium-ion battery materials	Greet dataset used	Amount per 1 kg
Copper wire	Cotton Paper Production - Pathway	0,264
Wrought aluminium	Average wrought aluminium	0,268
Lipf6	LiPF6 Production (Battery Materials)	0,011
Ethylene carbonate	Ethylene Carbonate Production (Battery Materials)	0,030
Dimethyl carbonate	Dimethyl Carbonate Production (Battery Materials)	0,030
Polypropylene	Final PP Product: Combined	0,012
High-density polyethylene	Final HDPE Product: Combined	0,005
Polyethylene terephthalate	Final PET Product: Combined	0,003
Steel	Steel Production from FIT100%H2 EAF Mix	0,006
Glass fibber	Glass Fibber Production	0,018
Power train coolant	Engine/Powertrain coolant from ethylene glycol	0,072
Battery management system	Battery Management System Production (Battery Materials)	0,042
NMC 622	Production of NMC(622)	0,145
n-menthyk-2-pyrrolidone	N-Methyl-2-pyrrolidone Production (Battery Materials)	0,001

Table 6. Lithium-ion battery for the CaetanoBus H2 City Gold materials and amounts per 1 kg of battery (Source: (Argonne National Laboratory, 2022)).

4.2.1.4 Electric motor and transmission system

Regarding these two parts, it was assumed that both bus model has the same electric motor and transmission system. Mainly due to the lack of information of these two components. Nonetheless, Nordelof, et al. (2019) commented that for the Volvo 7900 series powertrain, the weight was 3844 kg. Therefore, it was assumed this weight in both model. Regarding the transmission system, no information was found in any article o paper, so it was assumed to have a weight of 1.000 kg.

Regarding the materials compositions for the two components, it was assumed the Greet background datasets called *MHDV: Combination Long-Haul Truck - Electric - Traction Motor – Process"* for the electric motor and *MHDV: Combination Short-Haul Truck - Transmission (ICEV, HEV, EV, FCV) – Process*" for the transmission system (Argonne National Laboratory, 2022).

The materials and the related amount for 1 kg of electric motor were the following (Argonne National Laboratory, 2022):

Greet dataset used	Amount per 1 kg
Average Steel	0,361
Average Cast Aluminium	0,361
Copper Wire	0,278

Table 7. Electric motor materials and related amounts per 1 kg of electric motor (Source: (Argonne National Laboratory, 2022)).

Regarding the transition system the materials and the related amount for 1 kg of transmission were the following (Argonne National Laboratory, 2022):

Greet dataset used	Amount per 1 kg
Average Steel	0,8625
Average Cast Aluminium	0,0001
Average Wrought Aluminium	0,0007
Final Iron Product (combined)	0,0705
Final Average Rubber Product: Combined	0,0063
Final Average Plastic Product: Combined	0,0541
Copper Wire	0,0035
Brass Production - Pathway	0,0005
Magnet Production - Pathway	0,0017

Table 8. Transmission system materials and related amounts per 1 kg of transmission system (Source: (Argonne National Laboratory, 2022)).

4.2.1.5 Fuel cell stack

As commented before, the components of the FCS are based on Santesteban Garbe (2020) comprehensive analysis of the Mirai's FCS. It is formed by the next subcomponents:

- The Membrane electrode. Which is composed by a catalysed membrane, a catalyst and two gas diffusion layers (GDL) (Toyota, 2018) (Santesteban Garbe, 2020). Concretely, it is formed by seven layers: an anode GDL, a anode MPL, anode CL, a membrane, a cathode CL, a cathode MPL and cathode GDL (Santesteban Garbe, 2020).

  The former diced the reduction and oxidation reactions taking place in the cell by separating them in two. Additionally, it is responsible to only let the hydrogen protons pass through and make the electrons divert to other circuit (Santesteban Garbe, 2020).The catalyst layer benefit the electromechanical reaction to occur (Toyota, 2018) (Santesteban Garbe, 2020). The later (GDL) plays the roll of mediator and support and maintain a constant flow of the hydrogen to the catalyst layer (Toyota, 2018).
- Bipolar plates. This component by means of flow-field channels distribute the oxidant among the active areas (Santesteban Garbe, 2020). It also ease the heat and water managements, carry the electrical current from the cell and separates the divide different cells in the FCS (Santesteban Garbe, 2020).
- Endplates and collector. The former are made to maintain the single cells lined up and compressed in a stacked shape along with the compression bands (Santesteban Garbe, 2020). Finally, the collector controls the intake and exhaust flows.

4.2.1.5.1 Membrane

The Nafion is the most common used PEM for fuel cell stacks, based on perfluorosulfonic acid. The assumed membrane is set to be a dispersion cast membrane NRE-211 (Santesteban Garbe, 2020). Therefore, the materials that compose the membrane are tetrafluoroethylene (TFE), sulphuric trioxide and expanded PTFE (ePTFE).

Consequently, the weight of the membrane was assumed to be 4,5 kg, based on Santesteban Garbe (2020) and by applying the conversion factor. The components, the datasets of Greet used (Argonne National Laboratory, 2022) and the related amount for 1 kg of membrane were the following:

Membrane materials	Greet dataset used	Amount per 1 kg
Tetrafluoroethylene (TFE)	PTFE Production	0,867
Sulphuric trioxide	Sulphuric Acid Production	0,041
Expanded PTFE (ePTFE)	PTFE Production	0,091

Table 9. Membrane materials for the CaetanoBus H2 City Gold and related amounts per 1 kg of membrane (Source: (Santesteban Garbe, 2020) and (Argonne National Laboratory, 2022)).

4.2.1.5.2 Gas diffusion layer

This layer is normally produced of different materials, such as woven or non-woven carbon fibber cloth coated with a hydrophobic polytetrafluoroethylene (PTFE) agent (El-kharouf, et al., 2012). Besides, as an interface between large and small porous from the GDL and the catalyst a micro-porous layer if carbon graphite particles and PTF binder is installed (Santesteban Garbe, 2020).

Therefore, the GDL is composed by a Macro porous layer mixed with PTFE, a micro-porous layer also mixed with PTF and solvent. Hence, the gas diffusion layer was assumed to weight 12 kg approximately. This weight is based on Santesteban Garbe (2020) and by applying the conversion factor. The components, the datasets of Greet used (Argonne National Laboratory, 2022) and the related amount for 1 kg of GDL were the following:

Gas Diffusion Layer (GDL) materials	Greet dataset used	Amount per 1 kg
Macroporous layer (MPL)	Final Carbon Fibber-Reinforced Plastic Product for General Use: Combined	0,702
PTFE (for MPL)	PTFE Production	0,057

Gas Diffusion Layer (GDL) materials	Greet dataset used	Amount per 1 kg
Microporous layer (MiPL)	Activated carbon production- Coal based	0,172
PTFE (for MiPL)	PTFE Production	0,054
Solvent	Sodium acetate production pathway	0,015

Table 10. Gas diffusion layer materials for the CaetanoBus H2 City Gold and related amounts per 1 kg of GDL (Source: (Santesteban Garbe, 2020) and (Argonne National Laboratory, 2022)).

4.2.1.5.3 Catalyst

The catalyst is a complex part of the fuel cell stack. Apart from the aspects commented before, the catalyst to obtain a better dispersion of the catalyst particles and hence a better catalyst activity and mass transport is supported on a porous conductive material (i.e. carbon black) (Santesteban Garbe, 2020). Hence, the materials of the catalyst are Pt/c, carbon black, Nafion (PFSA) and methanol. Platinum and recycled platinum are also materials used in the catalyst layer (Santesteban Garbe, 2020).

The weight of the catalyst layer was assumed to be approximately 1 kg (based on Santesteban Garbe (2020) and by applying the conversion factor). Finally, the list of materials, the datasets of Greet used (Argonne National Laboratory, 2022) and the related amount for 1 kg of catalyst were the following:

Catalyst	Greet dataset used	Amount per 1 kg
Platinum	Platinum Production In North America (Mass Allocation)	0,100
Recycled platinum	Platinum Production In North America (Mass Allocation)	0,013
Carbon particles	Activated carbon production- Coal based	0,039
Polytetrafluoroethylene (PTFE)	PTFE Production	0,004
Solvent	Sodium acetate production pathway	0,843

Table 11. Catalyst layer materials for the CaetanoBus H2 City Gold and related amounts per 1 kg of catalyst layer (Source: (Santesteban Garbe, 2020) and (Argonne National Laboratory, 2022)).

4.2.1.5.4 Bipolar plates.

It is an important component in relation to the overall weight, so it used to be made of lightweight materials. Such as non-porous graphite, metal alloys or polymer composite materials (Santesteban Garbe, 2020). Therefore, for this case and following with the materials composition given by Santesteban Garbe (2020), the BPP were supposed to be made injection-moulded graphite composite (stainless steel, titanium nitride and graphite) and the gaskets that sail to keep it stacked were assumed to be made epoxy resin.

The weight of the bipolar plates was assumed to be 145 kg, based on Santesteban Garbe (2020) and by applying the conversion factor. The components and the related amount for 1 kg of BPP were the following:

Bipolar Plates (BPP) materials	Greet dataset used	Amount per 1 kg
Stainless steel	Stainless Steel Production	0,824
Titanium nitride (TiN)	Titanium Production (Virgin)	0,082
Graphite	Graphite Production (Battery Materials)	0,082
Screen Printed Gasket	Epoxy Resin	0,011

Table 12. Bipolar plates for the CaetanoBus H2 City Gold materials and amounts per 1 kg of BPP (Source: (Santesteban Garbe, 2020) and (Argonne National Laboratory, 2022)).

4.2.1.5.5 Endplates and collector

Following the assumptions made by Santesteban Garbe (2020), the materials used to produce the endplates are glass fibber, epoxy and stainless steel for compression straps (Santesteban Garbe, 2020). Regarding the collector, it was assumed to be made of copper (Santesteban Garbe, 2020).

The weight of the pack of endplates and collector were assumed to be 55 kg, (based on Santesteban Garbe (2020) and by applying the conversion factor). Finally, the list of materials, the datasets of Greet used (Argonne National Laboratory, 2022) and the related amount for 1 kg of endplates and collector were the following:

Endplate & Collector materials	Greet dataset used	Amount per 1 kg
Glass fibre (endplate)	Glass Fibber Production	0,100
Epoxy (endplate)	Epoxy Resin	0,100
Cooper (current collector)	Copper production	0,183
Stainless steel (compression bands)	Stainless Steel Production	0,117
Polypropylene (casing)	Final PP Product: Combined	0,500

Table 13. Endplate and collector materials for the CaetanoBus H2 City Gold and related amounts per 1 kg of endplate and collector (Source: (Santesteban Garbe, 2020) and (Argonne National Laboratory, 2022)).

4.2.1.5.6 Hydrogen storage tank

The hydrogen storage tank allows the vehicle to maintain safely the compressed hydrogen. The CaetanoBus have their tanks at a pressure of 350 bar and have a capacity of 37,5 kg (CaetanoBus, 2019).

Therefore, in order to meet the characteristics of the storage of the CaetanoBus, the hydrogen tanks were assumed to be the G2L-1 model produced by Toyota (Toyota, 2019). This tank has a mass of 136 kg and a hydrogen storage capacity of 9.4 kg (Toyota, 2019). In order the have the same capacity as CaetanoBus vehicle, it was assumed that four tanks were installed in the H2 City Gold bus.

The materials of the hydrogen tank were assumed high Density Polyethylene (HDPE), carbon fibber glass fibber and epoxy resin (Santesteban Garbe, 2020). With these materials, three different layers can be manufactured in order to safely storage the hydrogen (as it can be dangerous if exists any disruptive change in the pressure or temperature), a glass fibber reinforced layer, a polymer layer and a carbon fibber reinforced polymer.

Therefore, the weight of the four hydrogen storage tank were assumed to be 544 kg, based on Santesteban Garbe (2020) and by applying the conversion factor. In this case, the base hydrogen storage tank of Greet was used (Argonne National Laboratory, 2022). The list of materials, the datasets of Greet used (Argonne National Laboratory, 2022) and the related amount for 1 kg of endplates and collector were the following:

Greet dataset used	Amount per 1 kg
Final Carbon Fibber-Reinforced Plastic Product for High Pressure Vessels: Combined	0,656
Average Steel	0,092
Final Average Plastic Product: Combined	0,078
Other vehicle materials	0,039
Stainless Steel Production	0,081
Glass Fibber Reinforced Plastic Production Mix	0,045
Combined silicon (PV application)	0,010

Table 14. Hydrogen storage tank materials for the CaetanoBus H2 City Gold and related amounts per 1 kg of hydrogen storage tank (Source: (Santesteban Garbe, 2020) and (Argonne National Laboratory, 2022)).

4.2.1.5.7 Power control unit

The power control unit manage the all fuel cell system. In this case, the control unit was assumed to be composed by different electronic controllers and a battery management system. All the data, materials and the emission related to these two components were the default Greet dataset for the so called components (*Electronic controller (HEV, PHEV, EV, FCV) and Battery Management System Production (Battery Materials)*). The share for 1 kg of a FC management system of the two components are 0,74 kg of electronic components and 0,26 kg of a Battery management system. The total weight of FC management system was assumed approximately 11 kg (based on Santesteban Garbe (2020) and by applying the conversion factor).

4.2.1.5.8 Balance of plant (BoP)

The Balance of Plant is a management system that controls air, water, thermic and fuel systems in order to maintain a proper fuel cell operation. The former includes fibber filters and compressor expander module (CEM), the second includes a demister, the third includes high temperature radiators with a pump and coolant fluid, and the latest includes filters, a hydrogen recirculation blower and ejector (Santesteban Garbe, 2020). The weight of the BoP was assumed to be 330 kg (based on Santesteban Garbe (2020) and by applying the conversion factor).

The materials assumed by Santesteban Garbe (2020) and the Greet datasets used to meet the same materials characteristics are presented below:

Balance of Plant (BoP) materials	Greet dataset used	Amount per 1 kg
	Air Management	
Compression expansion motor (CEM)1	Traction Motor (HEV, PHEV, EV, FCV)	0,194
	Final Iron Product (combined)	0,083
Air filter	Final HDPE Product: Combined	0,018
Air ducting	Final HDPE Product: Combined	0,055
Mass flow sensor	Electronic Controller (HEV, PHEV, EV, FCV)	0,006
	Water Management	
Demister	Average Steel	0,040
	Heat Management	
High temperature loop (HTL)	Final Injection Moulded Rubber Product	0,129
Antifreeze liquid	Ethylene U.S. average production	0,074
	Fuel Management	
Ejectors	Average Cast Aluminium	0,001
Pipes	Average Steel	0,065
Valves	Hot Rolled Steel Product: Combined	0,019

Balance of Plant (BoP) materials	Greet dataset used	Amount per 1 kg
Inline filter	Hot Rolled Steel Product: Combined	0,013
Pressure switch	Average Wrought Aluminium	0,004
	Other Components	
Wiring	Copper Wire	0,181
Belly pan	Final Carbon Fibber-Reinforced Plastic Product for General Use: Combined	0,039
Mounting frames	Hot Rolled Steel Product: Combined	0,065
Fasteners	Hot Rolled Steel Product: Combined	0,013

Table 15. Balance of Planta materials for the CaetanoBus H2 City Gold and related amounts per 1 kg of BoP (Source: (Santesteban Garbe, 2020) and (Argonne National Laboratory, 2022)).

4.2.1.6 Assembly and distribution

The different components of the vehicles are assembly in different parts around the globe. This mainly means that, for expel, the whole bus of CaetanoBus is assemble in Portugal but the FCS is manufactured and assembled in Japan (Toyota, 2018). Therefore, the transportation process and the logistic chain of the models considered in this study also plays a relevant role in the carbon footprint of the vehicle.

Firstly, it is relevant to consider the cities where the bus models are assembled at final stage, just before being delivered to the client. In the case of the Volvo series 7900, the assembly of all vehicle components is executed in the Volvo Bus Facility in Wroclaw, Poland (Volvo Buses Global, 2020). On the contrary, the CaetanoBus H2 City Gold is assembled in the CaetanoBus Facility located in Porto, Portugal (Toyota Caetano Portugal, S.A, 2022).

Therefore, in order to obtain a global vision and an holistic perspective, the study takes into account were the different parts of the busses were assembled, assuming that the transportation processes can be made by vessel or heavy lorries (depending on the distance).

The former mode, is based on the vehicle called *Ocean Tanker”* (Argonne National Laboratory, 2022) and, independently of the component transported, the characteristics are the same. It was assumed that all the information related of average seed, load factor, payload, consumptions and fuel uses are from the background dataset from Greet (Argonne National Laboratory, 2022). However, as an overview, it is a vessel which can transport over 50.000 tons of payload, has an average speed of 32 km/h and a load factor of 80% and uses as *Heavy Fuel Oil (HFO 2.7%S)”* (Argonne National Laboratory, 2022).

The heavy lorry mode is based on *Heavy Heavy-Duty Truck*” (Argonne National Laboratory, 2022), and same as the Ocean tanker, the vehicle characteristics did not change depending the component transported. The characteristics therefore were assumed to be Greet datasets background (Argonne National Laboratory, 2022). Consequently, each lorry can transport 17 tons of each component, uses *Conventional Diesel from crude Oil for US refineries”* as a fuel and has an average fuel economy of 32,8 litres per 100 km when is fully loaded.

In addition, to model de assembly process it was used the base Greet assembly process called *MHDV: Combination Long-Haul Truck - Vehicle Assembly, Disposal & Recycling (ADR)”* (Argonne National Laboratory, 2022). However, it was modified to only take into account the assembly part. Therefore, the process is formed by *Heating assembly”*, *Material Handling assembly”*, *Welding assembly and compressed air assembly processes*” (Argonne National Laboratory, 2022). Which takes into account the electricity mix of each country involved in each component assembly.

Consequently, the electricity mix of assembly countries were modelled in order to observe properly the impacts of assembly the components in each country. Therefore, the mix for Sweden was assumed to be (Swedish Energy Agency, 2021):

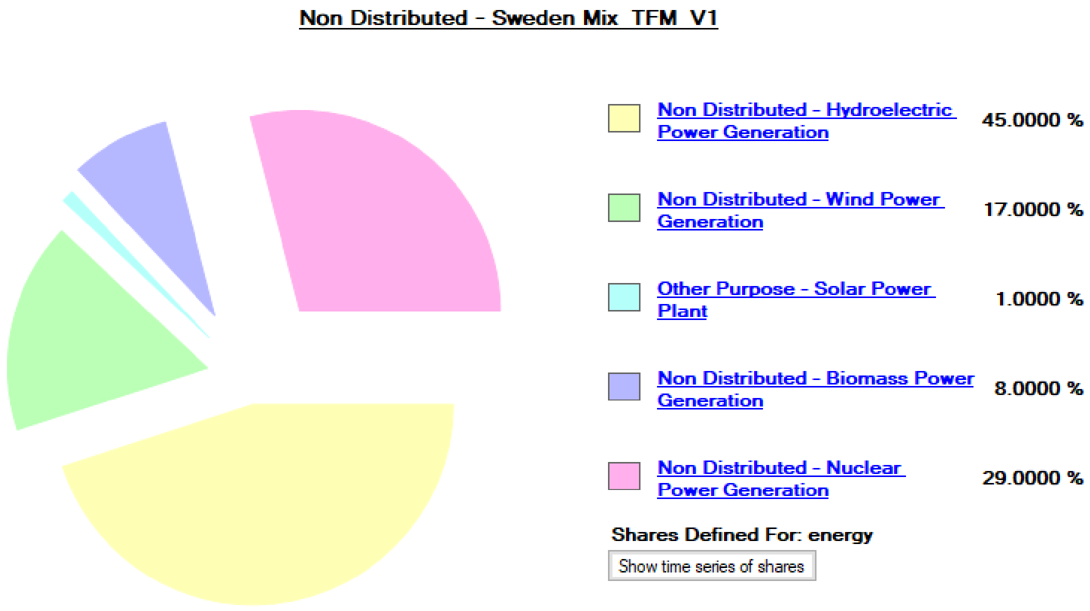


Figure 9. Sweden electricity mix (Source: (Swedish Energy Agency, 2021)).

The electricity mix for the USA was assumed to be Greet U.S. mix (Argonne National Laboratory, 2022):

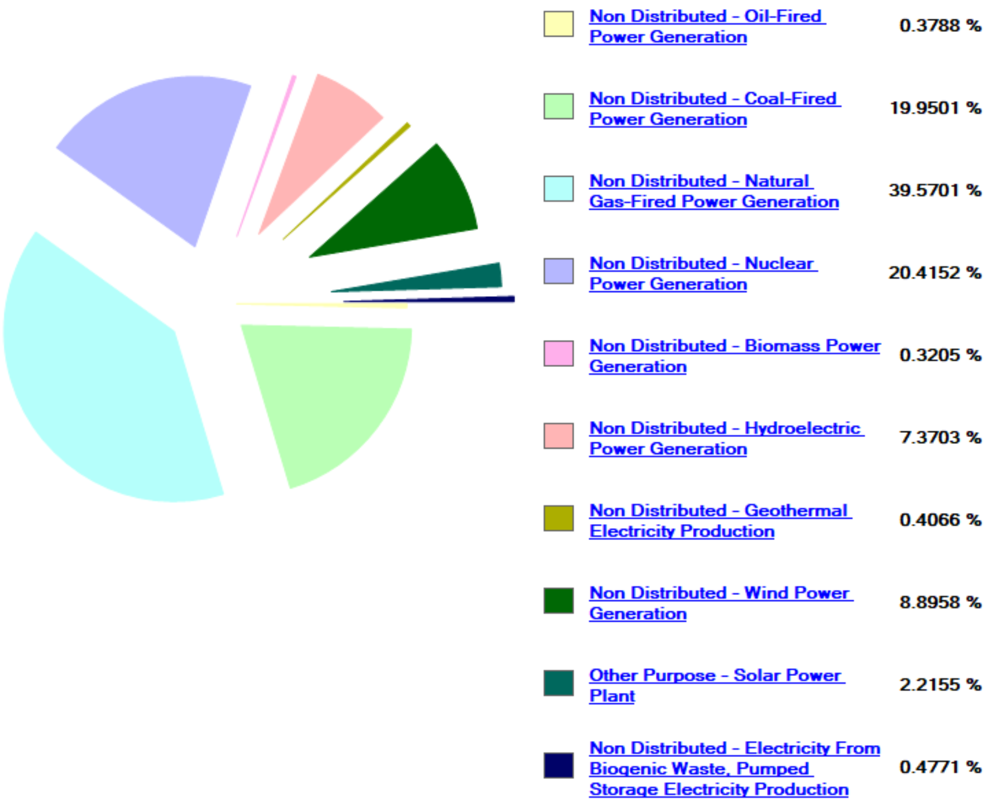
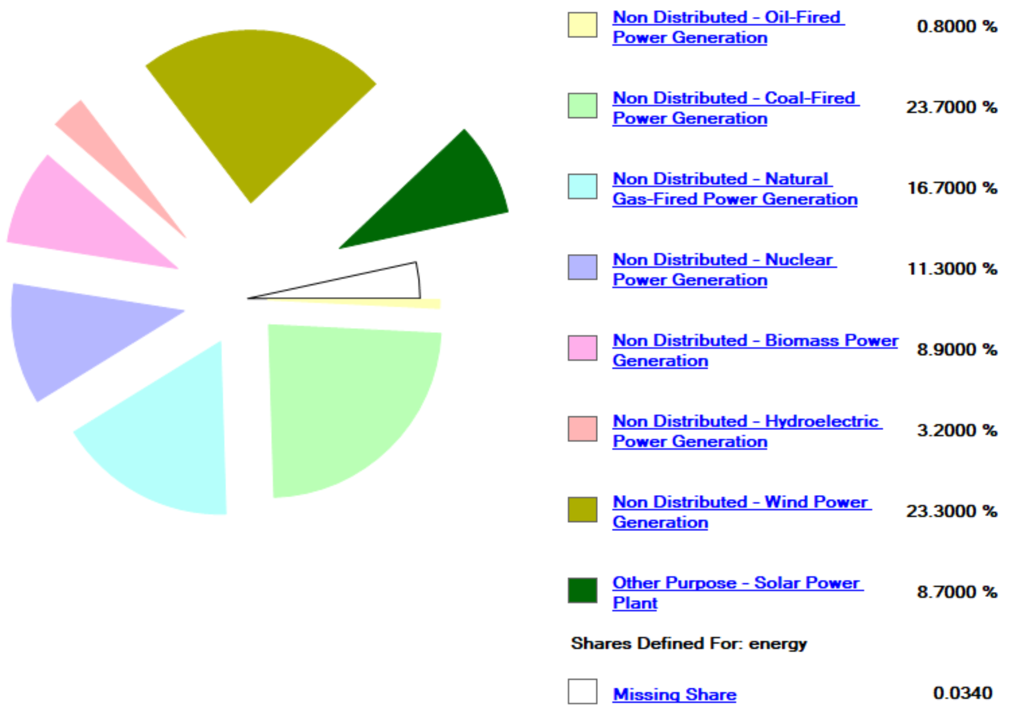


Figure 10. U.S electricity mix (Source: (Argonne National Laboratory, 2022)).

The Germany mix is assumed to be just as follows (Statistisches Bundesamt (Destatis), 2022):



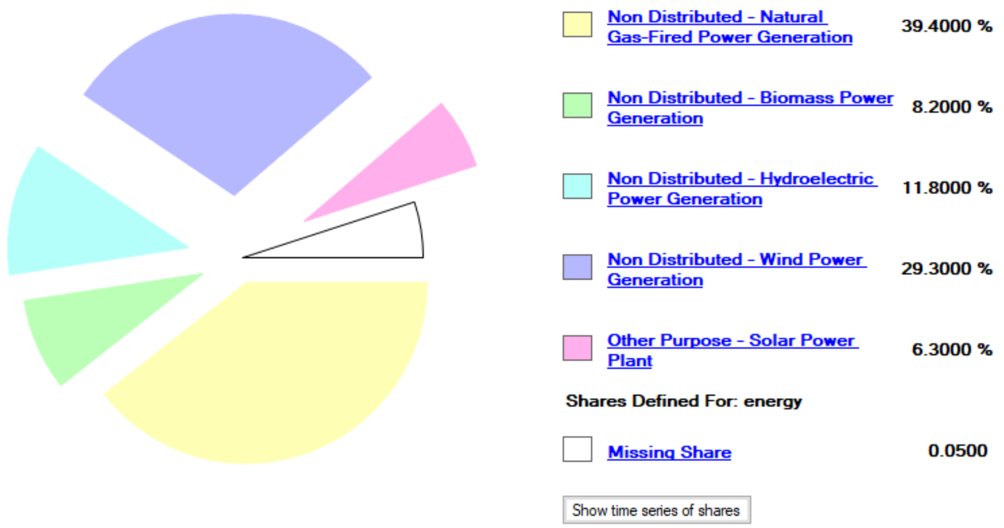
🟨	Non Distributed - Oil-Fired Power Generation	0.8000 %
🟩	Non Distributed - Coal-Fired Power Generation	23.7000 %
🟦	Non Distributed - Natural Gas-Fired Power Generation	16.7000 %
🟪	Non Distributed - Nuclear Power Generation	11.3000 %
🟪	Non Distributed - Biomass Power Generation	8.9000 %
🟥	Non Distributed - Hydroelectric Power Generation	3.2000 %
🟫	Non Distributed - Wind Power Generation	23.3000 %
🟩	Other Purpose - Solar Power Plant	8.7000 %

Shares Defined For: energy

☐	Missing Share	0.0340

Figure 11. Germany electricity mix (Source: (Statistisches Bundesamt (Destatis), 2022)*).*

The Portugal electricity mix was assumed the following (APREN, 2020), where 5% of the share was not specified:



🟨	Non Distributed - Natural Gas-Fired Power Generation	39.4000 %
🟩	Non Distributed - Biomass Power Generation	8.2000 %
🟦	Non Distributed - Hydroelectric Power Generation	11.8000 %
🟪	Non Distributed - Wind Power Generation	29.3000 %
🟪	Other Purpose - Solar Power Plant	6.3000 %

Shares Defined For: energy

☐	Missing Share	0.0500

Figure 12. Portugal electricity mix (Source: (APREN, 2020)).

The France electricity was assumed to be (RTE, 2022):

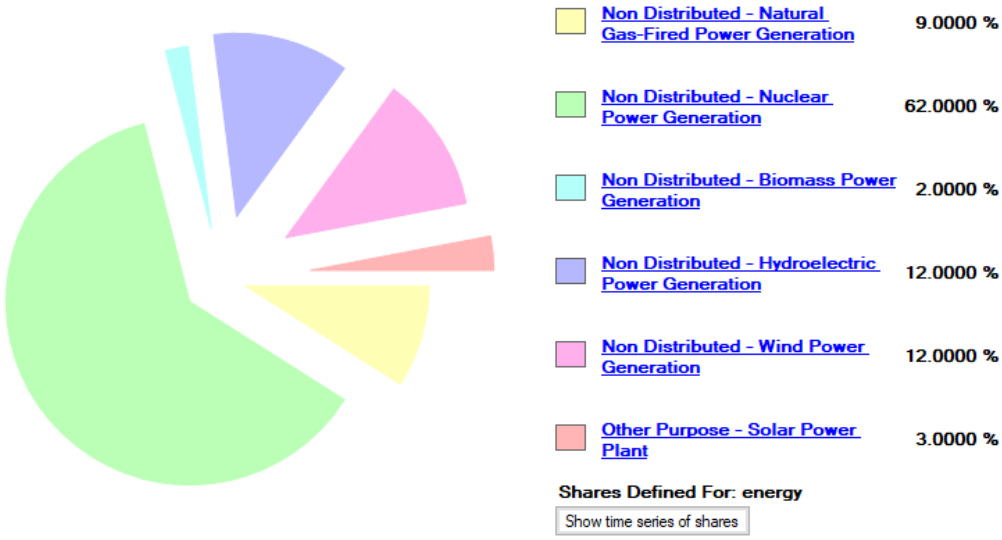


Figure 13. France electricity mix (Source: RTE, 2022).

Moreover, the final country of components assembly chain was Japan, which electricity mix was assumed as follows (Argonne National Laboratory, 2022):

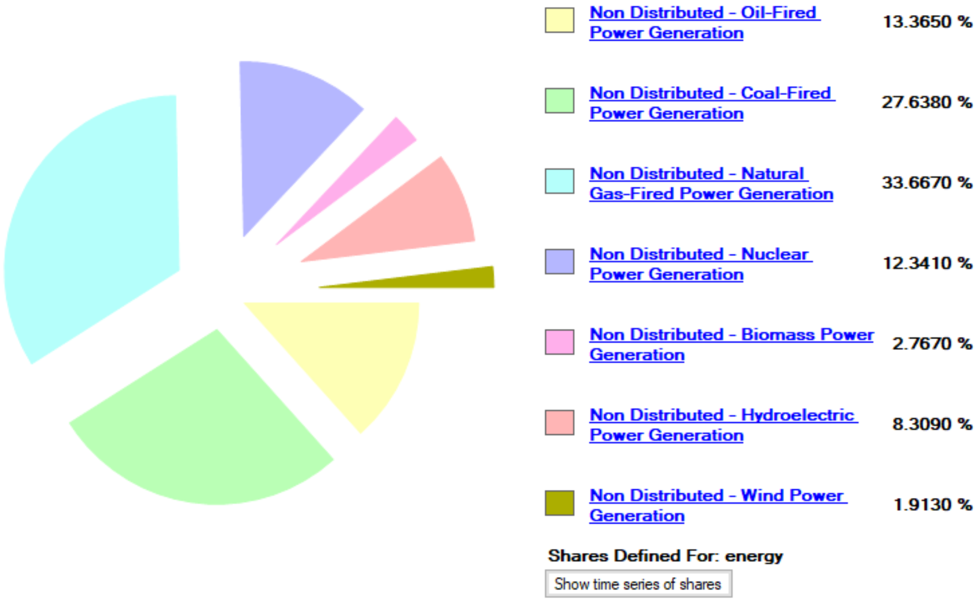


Figure 14. Japan electricity mix (Source: (Argonne National Laboratory, 2022)).

Finally, in the following table, it can be overserved (separated between FCB or AEB) the manufactured component, the country where the component is assembled, the assumed distance and mode used from the assembly facility and the main assembly factory of Volvo or CaetanoBus and the source used to extract the information about the assembly country:

Component	Assembly country	Distance to main assembly factory (km)	Modes used	Source
		AEB		
Chassis	Sweden (Boras)	790	Heavy Heavy-Duty Truck Ocean Tanker	(Volvo Buses Global, 2020)
Transmission system	Sweden (Koping)	1000	Heavy Heavy-Duty Truck Ocean Tanker	(Volvo Buses Global, 2020)
Battery	USA	7400	Heavy Heavy-Duty Truck Ocean Tanker	(Nordelof, et al., 2019)
Electric motor	Germany	500	Heavy Heavy-Duty Truck	(Nordelof, et al., 2019)
		FCB		
Chassis	Portugal	Information of assembly country was not found. Therefore, it was assumed to take place in Oporto.		
Transmission system	Portugal			
Battery	France	1000	Heavy Heavy-Duty Truck	(Forsee Power, 2022)
Electric motor	Germany	1900	Heavy Heavy-Duty Truck	(CaetanoBus, 2019)
Fuel cell stack	Japan	19504	Heavy Heavy-Duty Truck Ocean Tanker	(Toyota, 2018)

Table 16. Information related to components assembly (Source: own elaboration).

4.2.2 Use phase

In this stage, the driving and maintenances phases should be included for both vehicles. The stages have to consider the whole lifespan of each bus. Therefore, the lifespan for both bus model was assumed to be 800.000 km, based on Davide, et al (2022), which is about 12 years of services also regarding Volvo information (Volvo, 2019).

In relation to fuel economy, there are differences between models, as one is propelled all by electricity and the other with hydrogen. For the former, the information was based on TMB's Irizar 12 metres electric buses (TMB, 2019) real operating consumption of kWh per km for the year 2019. The electric bus is charged at night in the depot station and have an average fuel economy of 1,4 kWh/km (TMB, 2019). This value, had been transformed to miles per gallon gasoline equivalent to be able to introduced to Greet (by applying 1 kWh/100km is equal to 2.094 MPGe (Inch C. , 2022)).

On the other hand, with regard to the fuel cell bus, the manufacturer sated that the vehicle's fuel economy was 6kg of hydrogen per 100km. However, as this information is based on laboratory approximations and there are no data about the real consumption of the bus and to be in a conservative scenario, it was decided to use another realistic operating fuel economy. Therefore, based on Davide, et al. (2022), the fuel economy assumed to the H2 City Gold was 10,25 kgH2/100km. Even though it is a higher consumption rate compared to the manufacturer specifications, it is actually 41% smaller than CUTE project (Davide, et al., 2022).

As commented in the Fuel-cycle, the consumed hydrogen is modelled by different pathways (i.e. methane steam reforming, electrolysis with the Spain mix and on-site production with a renewable electricity mix). Therefore, the total amount of hydrogen and the related emission are calculated by using the fuel economy of the vehicle and its lifespan (Argonne National Laboratory, 2022).

However, regarding maintenance, Greet does not have any possible manner to consider this phase including all possible activities and reparations during the whole vehicle's lifespan. For that reason and due to the lack of in deep data about it in other scientific papers, during the maintenance stage it was only taken into account the replacement of different components (i.e. batteries or tires).

Greet (Argonne National Laboratory, 2022) however, take into account all upstream processes involved in the manufacturer and assembly of the different components replaced. This is logic, as each element requires the same amount of materials, energy and have to pass through all the processes of manufacture and assembly as the former components. Therefore, the environmental impacts of each replacement will be the same as the former manufacture process taken into account in the *Manufacture phase*".

Specifically, the components considered to be replaced during the operating phase of the vehicle were:

- Lithium-ion batteries. There was no available information from the manufacturers about the lifespan of the batteries. Therefore, the lifespan for the batteries were assumed to 220.000 km, based on (Garc´a Sánchez, et al., 2013). Hence, the batteries for the both vehicles were assumed to be changed 3 times during the operating phase.
- Fuel cell stack. Information form Toyota was not available neither. For that reason, and based on Davide, et al. (2022), the lifespan considered for the study case was 240.000 km. Therefore, the FCS was assumed to be replaced 2 times during the buss' lifespan.
- Tires and fluids. There was no information specially about these vehicle complements. Therefore, for the former, it was assumed to have a lifespan of 100.000 km, being replaced 7 time during all the operating face. Regarding the later, it was assumed that, during the buss' lifespan, they were required to be replaced at least 20 times (this was based on some other models done in Greet related to other vehicles (Argonne National Laboratory, 2022)).

4.2.3 End-of-life

This phase should take into account the disposal and recycling of all the parts of the different vehicles considered in this study. All the components should be separated and treated independently as all of the vehicle's elements are manufactured using different materials. Besides, the treatment of the batteries and fuel cells should be specially considered and studied, as it usually have the heaviest environmental impacts among other components (Nordelof, et al., 2019) (Davide, et al., 2022).

Nonetheless, Greet does not have and specific pathway for each component to model in deep this phase. However, it does have an approximation to the disposal stage, which can allow to account some impacts to the dismantle of the different components of the buses.

The pathway used in the study to for the disposal stage is called *MHDV: Combination Long-Haul Truck - Vehicle Disposal"* (Argonne National Laboratory, 2022). The process uses electricity to proceed; hence, the mix used was the Spain electricity mix. As it was supposed that two vehicles would end their operation cycle in the Spaniard, territory and it will not be transported back to its assembly facility (in Portugal o Poland).

It is important to take into account that the related environmental impact of this process were the same for each bus component, and the only difference were related to the weight of it.

Notwithstanding, it was considered relevant to add some recycling credits to the environmental impacts of the life cycle assessment. Hence, it was assumed in the calculations of the *end-of-life"* phase the related percentages of credits found by Davide, et al. (2022). The authors calculated these environmental credits by carrying out the average mix of the best available technologies and applying consequential LCAs (Davide, et al., 2022) (Nakatani, 2014). Finally, the percentages were determined by dividing the amount of credit for each environmental impact with the whole vehicle negative impact (i.e. the credits from CO_2 computed divided by all the CO_2 generated in the vehicle cycle, excluding use phase). The values used in this study can be found in the following table:

	ADP-f	**PMFP**	**GWP100**	**HOFP**	**TAP**
EOL credits	-41%	-60%	-28%	-42%	-69%

Table 17. EoL credits used in the present study (Source: (Davide, et al., 2022)).

However, rather than be considered as trustworthy values, in the study they are only taken into account as an approximation with illustration purposes. Which does not compute in the global LCA. The values are only gives an idea of how much the environmental impact can be reduced by a proper recycling process.

5 Life cycle impact assessment

Once the vehicle and fuel cycle are addressed, the following step to be done is assessing the magnitude of each component flow to the environmental impact related (Nordelof, et al., 2014). Concretely, life cycle impact assessment aim is to analyse each product system (i.e. the complete production and value chains) that make up each vehicle studied from an environmental perspective (Santesteban Garbe, 2020) by defining different impact categories and category indicators.

This methodology used in this assessment is applied due to its widely implementation in other related LCA literature and related papers (Miotti, et al., 2017) (Nordelof, et al., 2014) (Lemardelé, et al., 2022). In addition, it was considered relevant to follow the same methodology of other authors so that comparisons and further studies can be carried out based on the present assessment.

Therefore, in order to provide a properly defined and standard category impacts (i.e. the most relevant related to transportation and vehicles propulsion technologies), the present study took into account the calculation procedure defined in ReCiPe 2008 (Goedkoop, et al., 2009). It was a methodology motivated by Radbound Universitiet Nijmegen and CE Delft and developed by RIVM, CML and PRé consultants (Goedkoop, et al., 2009). The present methodology is based on harmonized category indicators which allows to compute the midpoint or endpoint environmental impact (Goedkoop, et al., 2009) by using other relevant methods such as Eco-indicator 99 and CML 2001 (Santesteban Garbe, 2020) (Goedkoop, et al., 2009).

Consequently, the following environmental impact categories, its related characterisation factor and units were used to assess the vehicle's life cycle assessment:

Impact category	Characterisation factor	Related unit
Climate change	Global Warming Potential	kg CO2 eq.
Terrestrial Acidification	Terrestrial Acidification Potential	kg SO2 eq.
Human health damage due to PM10	Particulate Matter Formation Potential	kg PM10 eq.

Impact category	Characterisation factor	Related unit
Human health damage due to ozone	Ozone Formation Potential	kg NMVOC eq.
Fossil fuel depletion	Fossil Fuel Depletion CF	kg oil eq.

Table 18. Impact categories and its characterisation factors" (Source: (Goedkoop, et al., 2009) (Santesteban Garbe, 2020)).

Finally, it is relevant to highlight that ReCiPe 2008 methodology includes other impact categories, such as Human Toxicity, Water Eutrophication, Metal Depletion, Ozone depletion, Ionising radiation or Land-use (Goedkoop, et al., 2009). Nonetheless, due to Greet's limitations to compute and determine other and more specific outputs for their life cycle assessment calculation, the number of impact categories considered was reduced.

5.1 Climate change

Climate change impact category is based on potential negative impacts that the product system –in this case the buses models- can produce over both human and environmental health (Goedkoop, et al., 2009).

The environmental mechanisms used to determine the negative impacts are based on four steps (Goedkoop, et al., 2009). Firstly, the radiative forcing is quantified by accounting the increments of the product system produces in the infrared radiative forcing over a period of time (Santesteban Garbe, 2020). This process uses IPCC equivalence factor to be able to gather with the same unit the negative impacts related to other contaminants, not only CO_2.

Secondly, the temperature effect. Which takes into account the residence time and radiative forcing of several other contaminants due to a temperature increase (Goedkoop, et al., 2009). Thirdly, the damage to human health is considered. To compute these impacts, ReCiPe take into account different publications done by WHO, WMO and UNEB, which studied how the health risk increases in relation with the temperature (Goedkoop, et al., 2009). Finally, the damage to ecosystem diversity is also addressed. The authors based their modelling in the work done by Thomas C.D called

Extinction risk from climate change" published in 2004, which predicts the extension of species on global scale due to climate change effects (Goedkoop, et al., 2009).

The characterisation factor of this category is called Global warming potential (GWP), which accumulates all the equivalent CO_2 generated by the product system (again, not only the direct CO_2 emissions) (Goedkoop, et al., 2009). In this stage, it is also important to evaluate the impacts with hierarchist perspective, as there have to be a trade-off between optimistic and conservative related to time period and other issues (Santesteban Garbe, 2020). Hence, for these impacts a 100-year time period is considered. It is also the most frequently used (referred in ISO 14044) (Goedkoop, et al., 2009).

Finally, the Intergovernmental Panel on Climate Change (IPCC) took into account different gases to include them in the climate change category. Therefore, standardizing the impact category. The Global Warming potential allows transforming the Greet results to common indicators used in ReCiPe methodology. These gases and their GWP equivalence can be found in the following table based on Fazio, et al. (2018):

Substance	Compartment	GWP100
Carbon dioxide	Air emission	1
Methane	Air emission	36,75
Carbon monoxide	Air emission	1,5712[12]

Table 19. CFs (in CO2-equivalents, with carbon feedbacks)" (Source: (Fazio, et al., 2018)).

5.2 Terrestrial acidification

This category takes into account the impacts produced by sulphates, nitrates, and phosphates in the acidity of the soil (Goedkoop, et al., 2009). As each specie requires an optimum soil acidity, any change of it can produce several harmful effects. According to Goedkoop, et al., (2009), the most acidifying emissions are NOx, NH_3, and SO_2.

The calculations of this category are based on three main factors. The first, the fate factor, which account for the environmental persistence of any acidifying substance (Goedkoop, et al., 2009). The second is the effect factor, which account the ecosystem damage due to an acidifying substance (Goedkoop, et al., 2009). Finally, the base saturation, which is used to express acidity and evaluate any change of it (Goedkoop, et al., 2009).

The terrestrial acidification potential (TAP) is indicated in kg of SO_2 equivalents and it considers the three main acidifying pollutants commented before (NO_x, NH_3, and SO_2) (Goedkoop, et al., 2009). TAP allows to transform the Greet results to common indicators. Similarly, to the climate change category, a 100-year time period is considered in order to determine the TAP. It can be observed in the following table based on Goedkoop, et al. (2009):

Pollutant	TAP factor
NO_x to air	0,56
NH_3 to air	2,45
SO_2 to air	1,00

Table 20. Terrestrial acidification potentials for Europe (in kg SO2-equivalents/kg)" (Source: (Goedkoop, et al., 2009)).

Even though there are three main pollutants, in this study NO_x is only taken into account (and its related TAP factor to obtain the SO_2 equivalents). It is mainly because Greet does not have outputs for the other three pollutants, so a proper analysis of them are not possible.

5.3 Human health damage due to PM10 and Photochemical Oxidant Formation

This category is addressed to the human health damage in the upper part of the airways and lungs produced by organic and inorganic particles with a diameter less than 10 µm (Goedkoop, et al., 2009) once inhaled. According to Goedkoop, et al., (2009) and WHO (2003) the three principal pollutants that formed PM10 particles are sulphur dioxide (SO_2), ammonia (NH_3), and nitrogen oxides (NO_x).

Regarding Photochemical Oxidant Formation category accounts for the zone generated by photochemical reactions of NO_x and Non Methane Volatile Organic Compounds

(NMVOCs) which depend on meteorological conditions and concentrations of the pollutants commented before (Goedkoop, et al., 2009). It is considered as ozone is potentially harmful by inflaming airways and damage lungs (Goedkoop, et al., 2009) and therefore produce pulmonary disease.

Similarly, to terrestrial acidification, the calculations of both categories are based on three factors. The fate factor, which is the marginal change in intake rate of a certain pollutant because of a marginal change in emission of the other pollutant that equals the intake factor of the former pollutant for the *European pollution*" (Goedkoop, et al., 2009). Secondly, the effect factor, which relates the marginal alterations in intake to marginal alterations in the *Attributable Burden"* of a certain pollutant of developing a disease because of being exposed to the pollutant during a year (Goedkoop, et al., 2009). Finally, the damage factor is related to the bonds that marginal alterations that the attributable burden have with marginal alterations in *DALY*" (Goedkoop, et al., 2009).

Therefore, human health damage due to PM10 is calculating by summing all the kg PM10 equivalents of the main pollutants (NO_x, NH_3, and SO_2) and the PM10 particles directly determined (Goedkoop, et al., 2009). As commented before, due to Greet limitations in the results extraction of pollutants, only NO_x was considered as well as the amount PM10 computed directly by Greet (which are not related to the pollutants commented) (Argonne National Laboratory, 2022). The particulate matter formation potential (PMFP) (to transform the Greet results to common indicators) of each pollutant can be observed in the following table based on Goedkoop, et al. (2009):

Emitted substance	Particulate Matter Formation Potential (PM10-eq/kg)
PM to air	1,00
NH3 to air	0,31
NOx to air	0,21
SO2 to air	0,19

Table 21. Midpoint Characterization Factors for particulate matter formation (Source: (Goedkoop, et al., 2009)).

Regarding photochemical oxidant formation is determined by summing the ozone formation potential (OFP) related to NO_x and non-methane volatile organic compounds

(NMVOC) (Goedkoop, et al., 2009). Nonetheless, Greet does not give NMVOC as a result. Consequently, only NO_x was considered. The category results are given by kg of NMVOC-eq obtained by the following OFP (to transform the Greet results to common indicators) based on Goedkoop, et al. (2009):

Emitted substance	Ozone Formation Potential NMVOC-eq/kg
NOx to air	1,00
NMVOC to air	1,00

Table 22. Midpoint Characterization Factors for tropospheric ozone formation of substance x" (Source: (Goedkoop, et al., 2009)).

5.4 Fuel fossil depletion

This impact category takes into account the depletion of fuel fossil –which contains hydrocarbons- that considers from volatile materials, to liquid petrol, to non-volatile materials during the all vehicle life cycle (Goedkoop, et al., 2009).

The characterisation factor is related to the energy content and it can be computed as the ratio between the cumulative energy demand indicator for a certain non-renewable source (MJ/unit of that source) and the reference oil source indicator of cumulative energy demand (MJ/oil) (Goedkoop, et al., 2009). It is important to highlight that Goedkoop, et al., (2009) used the factors considered in econinvent database while developing the fuel fossil depletion category. Therefore, there would be fossil fuels that Greet does not consider.

The results of this impact category are given in kg of oil equivalent that quantifies the depletion of the different fossil fuel depletions. The reference resource chosen was *Oil, crude, feedstock, 42 MJ per kg, in ground"* (Goedkoop, et al., 2009). In that way, each resource can be expressed in the same unit even though there are independent. The Fossil Fuel Depletion characterisation can be found in the following table based on Goedkoop, et al. (2009):

Resource	Fossil fuel depletion CF	Unit used
Coal, 18 MJ per kg, in ground	4.29E–01	kg oil-eq/kg
Coal, 26.4 MJ per kg, in ground	6.29E–01	kg oil-eq/kg
Coal, 29.3 MJ per kg, in ground	6.98E–01	kg oil-eq/kg
Coal, brown, 10 MJ per kg, in ground	2.38E–01	kg oil-eq/kg
Coal, brown, 8 MJ per kg, in ground	1.90E–01	kg oil-eq/kg
Coal, brown, in ground	2.36E–01	kg oil-eq/kg
Coal, feedstock, 26.4 MJ per kg, in ground	6.29E–01	kg oil-eq/kg
Coal, hard, unspecified, in ground	4.55E–01	kg oil-eq/kg
Energy, from coal	2.38E–02	kg oil-eq/MJ
Energy, from coal, brown	2.38E–02	kg oil-eq/MJ
Energy, from gas, natural	2.38E–02	kg oil-eq/MJ
Energy, from oil	2.38E–02	kg oil-eq/MJ
Energy, from peat	2.38E–02	kg oil-eq/MJ
Energy, from sulfur	2.38E–02	kg oil-eq/MJ
Gas, mine, off-gas, process, coal mining/kg	1.19E+00	kg oil-eq/kg
Gas, mine, off-gas, process, coal mining/m^3	9.48E–01	kg oil-eq/m^3
Gas, natural, 30.3 MJ per kg, in ground	7.21E–01	kg oil-eq/kg
Gas, natural, 35 MJ per m^3, in ground	8.33E–01	kg oil-eq/m^3
Gas, natural, 36.6 MJ per m^3, in ground	8.71E–01	kg oil-eq/m^3
Gas, natural, 46.8 MJ per kg, in ground	1.11E+00	kg oil-eq/kg
Gas, natural, feedstock, 35 MJ per m^3, in ground	8.33E–01	kg oil-eq/m^3
Gas, natural, feedstock, 46.8 MJ per kg, in ground	1.11E+00	kg oil-eq/kg
Gas, natural, in ground	9.12E–01	kg oil-eq/m^3
Gas, off-gas, oil production, in ground	9.48E–01	kg oil-eq/m^3
Gas, petroleum, 35 MJ per m^3, in ground	8.33E–01	kg oil-eq/m^3
Methane	8.55E–01	kg oil-eq/kg
Oil, crude, 38400 MJ per m^3, in ground	9.14E+02	kg oil-eq/m^3
Oil, crude, 41 MJ per kg, in ground	9.76E–01	kg oil-eq/kg
Oil, crude, 42 MJ per kg, in ground	1.00E+00	kg oil-eq/kg
Oil, crude, 42.6 MJ per kg, in ground	1.01E+00	kg oil-eq/kg
Oil, crude, 42.7 MJ per kg, in ground	1.02E+00	kg oil-eq/kg
Oil, crude, feedstock, 41 MJ per kg, in ground	9.76E–01	kg oil-eq/kg
Oil, crude, feedstock, 42 MJ per kg, in ground	1.00E+00	kg oil-eq/kg
Oil, crude, in ground	1.09E+00	kg oil-eq/kg

Table 23. Midpoint characterisation factors (individualist, hierarchist and egalitarian perspective) for fossil depletion" (Source: (Goedkoop, et al., 2009)*).*

6 Results

Once commented the vehicle (by differencing all the vehicle's components) and fuel cycle and the impact categories evaluated, the results for both Volvo 7900 Series electric bus and the CaetanoBus H2 City Gold fuel cell vehicle can be presented. The environmental impacts are gathered firstly by accounting the whole buses life cycle, and after by separating the different phases which forms the vehicle cycle (including the fuel cycle related to the operational stage).

The results are related to the buses lifespan, a total of 800.000 km (Davide, et al., 2022). All the impact results are presented with their reference unit (please, see Table 18. Impact categories and its characterisation factors" (Source:). This reference unit is given by kg of pollutant equivalent per 100 km driven. Hence, the total vehicle cycle is obtained by multiply the results by the ratio between the kilometres lifespan and the related 100 km driven.

Consequently, the results obtained are directly attributed to the two different bus models studied which independent regarding other product systems. However, it is relevant to highlight that the present results are based on an attributional modelling framework. Due to it applies impacts responsibilities and other attributes (which sometimes depends on the society evaluated and cultural differences (Goedkoop, et al., 2009)) (Santesteban Garbe, 2020). This implies some grade of subjectivity as it isolates and limits the interaction of the vehicle product system with other product chains, which differs from reality where all the products systems are somehow interconnected between each other.

6.1 Whole life cycle

The results regarding the environmental impacts of the whole life cycle of CaetanoBus H2 City Gold and Volvo 7900 Series are presented in Figure 15. CaetanoBus H2 whole life cycle results (Source: own elaboration). and Figure 16. Volvo 7900 Series whole life cycle result (Source: own elaboration)., respectively. For both figures, the environmental categories impact is presented individually and attributed by the related contribution rates of each vehicle phase. Relevant to comment, the use phase is divided in this case by the well to pump fuel impact (which is the environmental impacts regarding the production cycle of both hydrogen and electricity) and the maintenance parts (which includes the replacements of different vehicle components).

Firstly, regarding the CaetanoBus, it can be observed that well to pump (the hydrogen production) stage has the biggest share in all the environmental impacts hence generating the most potential environmental impact. Followed by the manufacture phase and maintenance phase. The EOL does not affect significantly in neither of the categories, being negligible.

The influence of the well to pump is due to how the hydrogen is produced. Since in the base scenario is produced via natural gas (being grey hydrogen) the environmental impacts are consequently negative. The natural gas plays a negative role caused by its fossil origin (in the following chapters, a sensitivity analysis of hydrogen production will be done).

In terms of share, the hydrogen production contributes an 83% to the global warming potential impacts, which is a total of 110,6 kg CO_2 eq./100km. The other phases affect less to this impact, being the manufacture the most significantly with a total of 11,4 kg CO_2 eq./100 km (a total share of 8%). Finally, the maintenance (which considers the replacements of batteries, fuel cell stack, tires and fluids by adding all the upstream process) is also relevant with a total share of an 5% and a 6,7 kg CO_2 eq./100km.

Regarding the terrestrial acidification, the share of the WTP is also significant, being 62% of the total impact category. This share means a total of 0,018 kg of SO_2 eq./100 km, which is a value considerably higher than other phases. Similar to GWP, the manufacture phase is the second that affects the most this category, with a total share of a 22% and a 0,06 kg SO_2 eq./100km.

The Particulate Matter Formation Potential follows the same trend, being the WTP the phase that most affect. The share is equal to 53 % (the smaller share between the different categories) and a total of 0,01 kg PM10 eq./100km. It is followed by the manufacture and maintenance phases, with a total of 0,008 kg PM10 eq./100km (22% of share) and 0,004 kg PM10 eq./100km (17% of the total impact), respectively.

The Ozone Formation Potential and Fossil fuel depletions are mainly influenced by hydrogen production as well. The shares for the former and its related amounts are the following: the WTP has a total share of 62% and 0,031 kg NMVOC/100km, the manufacture phase and maintenance phase have 22% and 15% of share respectively, which means a total of 0,011 kg NMVOC/100km and 0,007 kg NMVOC/100km. Regarding the latest, similar impacts are observed: WTP generates 75,3 kg oil eq./100km and a share of 63, It is follow by again the manufacture and maintenance phase. However, in this case, the share is similar, 19 % and 18 % respectively. That means a generation of 23,0 kg oil eq./100km for the former, and 21,5 kg oil eq./100km for the latest.

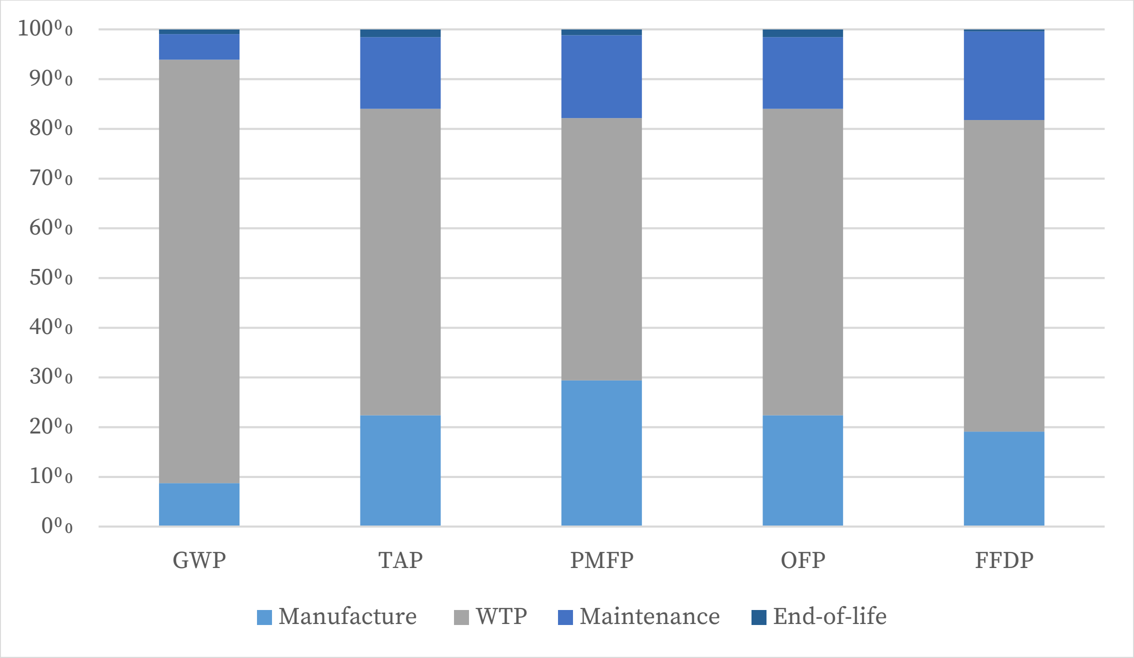


Figure 15. CaetanoBus H2 whole life cycle results (Source: own elaboration).

The detailed results for the H2 City Gold bus can be seen in the following table:

Kg x eq./100km	**GWP**		**TAP**		**PMFP**		**OFP**		**FFDP**	
Manufacture	11.4	8%	0.006	22%	0.006	29%	0.011	22%	23.0	19%

Kg *x* eq./100km	GWP		TAP		PMFP		OFP		FFDP	
WTP	110.6	83%	0.018	62%	0.010	53%	0.031	62%	75.3	63%
Maintenance	6,7	5%	0.004	14%	0.003	17%	0.007	14%	21.5	18%
End-of-life	1.3	1%	0.000	2%	0.000	1%	0.001	2%	0.4	0%
Total	130.0	1.000	0.028	1.000	0.019	1.000	0.051	1.000	120.2	1.000
EOL credits	-37.5	-28%	-0.020	-69%	-0.012	-60%	-0.021	-42%	-49.3	-41%

Table 24. Detailed results for the whole life cycle of CaetanoBus H2 City Gold (Source: own elaboration).

In relation to the results obtained for the Volvo 7900 Series, the trend is similar. However, the whole impact of this vehicle is smaller than the CaetanoBus. This is mainly produced by the difference in the fuels used during the operational stage. Which gives an important aspect to be considered while deciding which bus use, as the process of produce the fuel is the most relevant for the environmental potential impacts (and also related to the cost of ownership, which will be evaluated in next chapters).

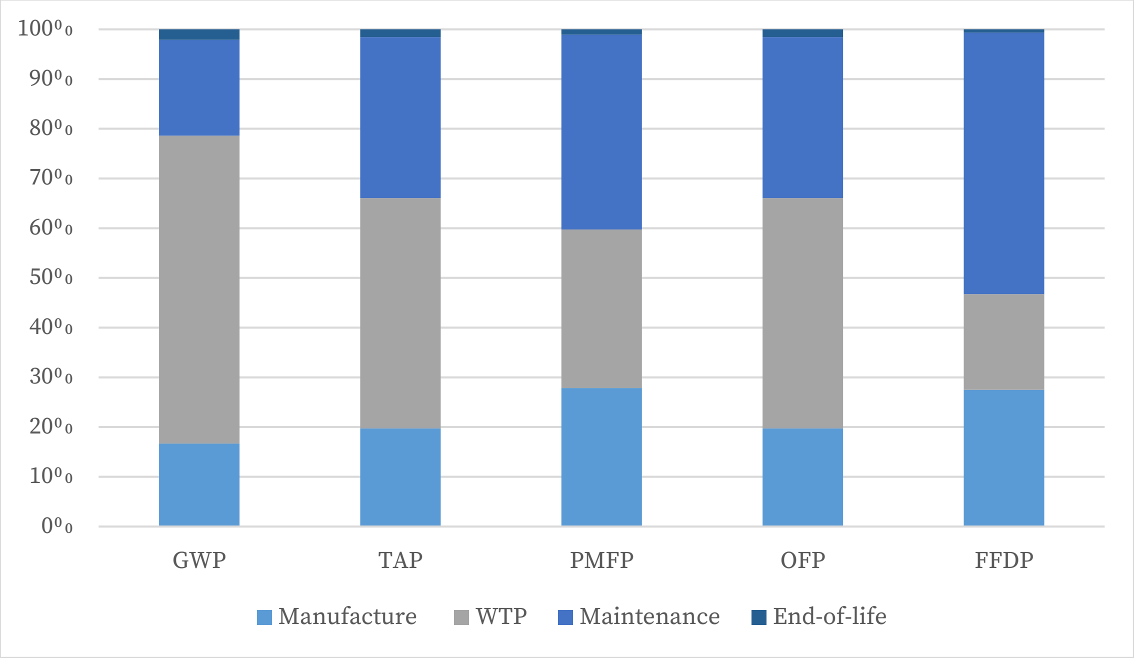


Figure 16. Volvo 7900 Series whole life cycle result (Source: own elaboration).

As an example, the Volvo has a Global warming potential of 60,69 kg CO_2 eq. /100 km but the CaetanoBus GWP is equivalent to 130 kg CO_2 eq. /100 km. Which more than the double. Again, this is mostly related to the fuel generation, as the hydrogen production is significant detrimental for the environment than the production of electricity (which in the case of Spain, has a relevant share of renewable energy resources and low CO_2 emissions production, i.e. nuclear plants). That effect can be also seen in the fuel depletion potential, where the WTP phase does have smaller share compared to the CaetanoBus, which is 19% compared to the 63% (12,87 kg oil eq./100km and 75,3 kg oil eq./100km respectively).

Nonetheless, in Volvo's case, the share of the manufacture and maintenance changes its trends. For CaetanoBus the former has more contribution, but for Volvo bus, the maintenance phase is more significant than the manufacture. It is mainly attributed to the fact that –as Volvo is a full electric vehicle- the batteries replacements play a significant role in the environmental impact potentials. Batteries life span are limited (around 220 km) which means a replacement of three times. Besides, the amount of batteries that the Volvo 7900 Series possess is much bigger than the CaetanoBus, adding more harmful impacts to the environment. The higher change of share, can be observed in the fossil fuel depletion, were the maintenance phase climbs up until the 53% of the total environmental impact potential, which is equivalent to 35,17 kg oil eq./100km.

The other phases have similar environmental impacts potentials. For example, regarding terrestrial acidification potential, WTP have a share of 46% with 0,013 kg SO_2 eq./100km and the maintenance phase have 32% of the total environmental potential impact, which is equivalent to 0,009 kg SO_2 eq./100km (it can be seen that the values obtained for the Volvo are smaller than the CaetanoBus except for the maintenance phase).

Kg *x* eq./100km	**GWP**		**TAP**		**PMFP**		**OFP**		**FFDP**	
Manufacture	10.13	17%	0.005	20%	0.006	28%	0.010	20%	18.39	28%
WTP	37.59	62%	0.013	46%	0.007	32%	0.023	46%	12.87	19%
Maintenance	11.71	19%	0.009	32%	0.008	39%	0.016	32%	35.17	53%
End-of-life	1.27	2%	0.000	2%	0.000	1%	0.001	2%	0.44	1%

Kg *x* eq./100km	GWP		TAP		PMFP		OFP		FFDP	
Total	60.69	100 %	0.028	100 %	0.021	100 %	0.050	100 %	66.87	100 %
EOL credits	-17.0	-28%	-0.019	-69%	-0.012	-60%	-0.021	-42%	-27.4	-41%

Table 25. Detailed results for the whole life cycle of Volvo 7900 Series (Source: own elaboration).

The following graphics show the differences between the Volvo 7900 Series and CaetanoBus H2 City Gold for each impact category:

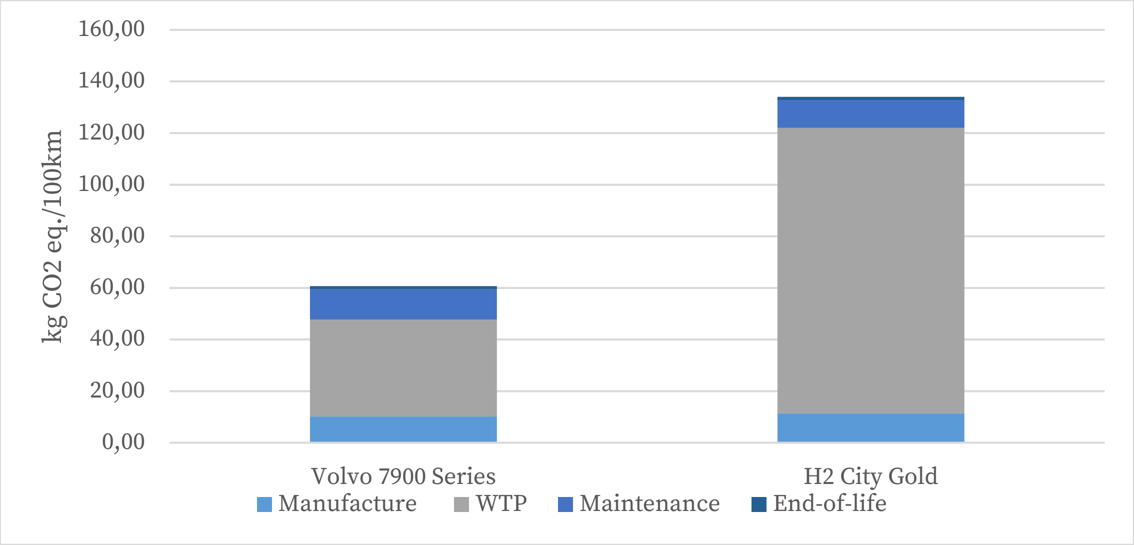


Figure 17. Differences between the two models for the GWP (Source: own elaboration).

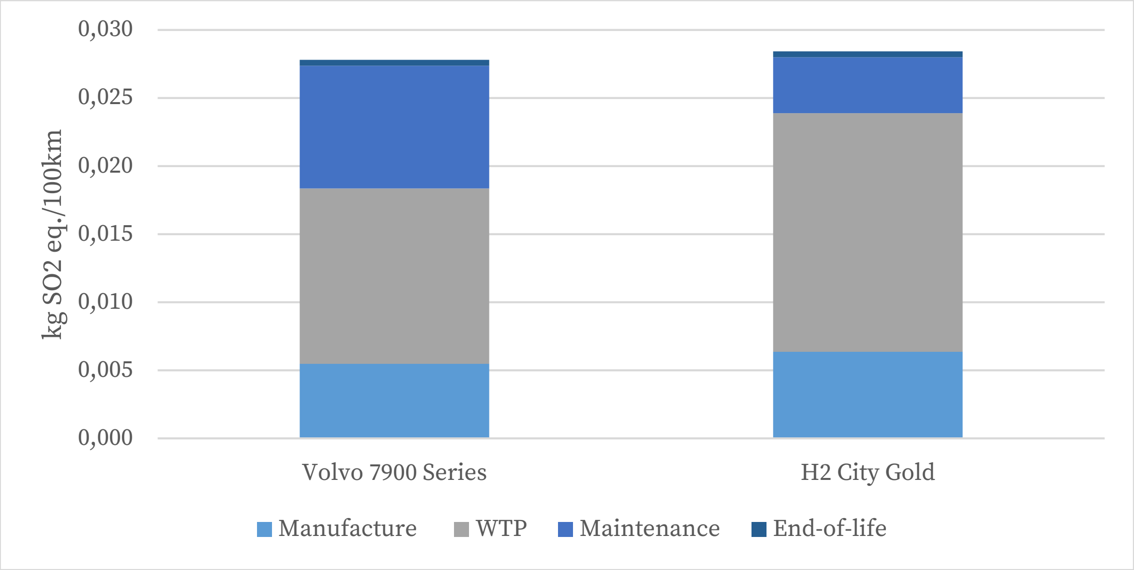


Figure 18. Differences between the two models for the TAP (Source: own elaboration).

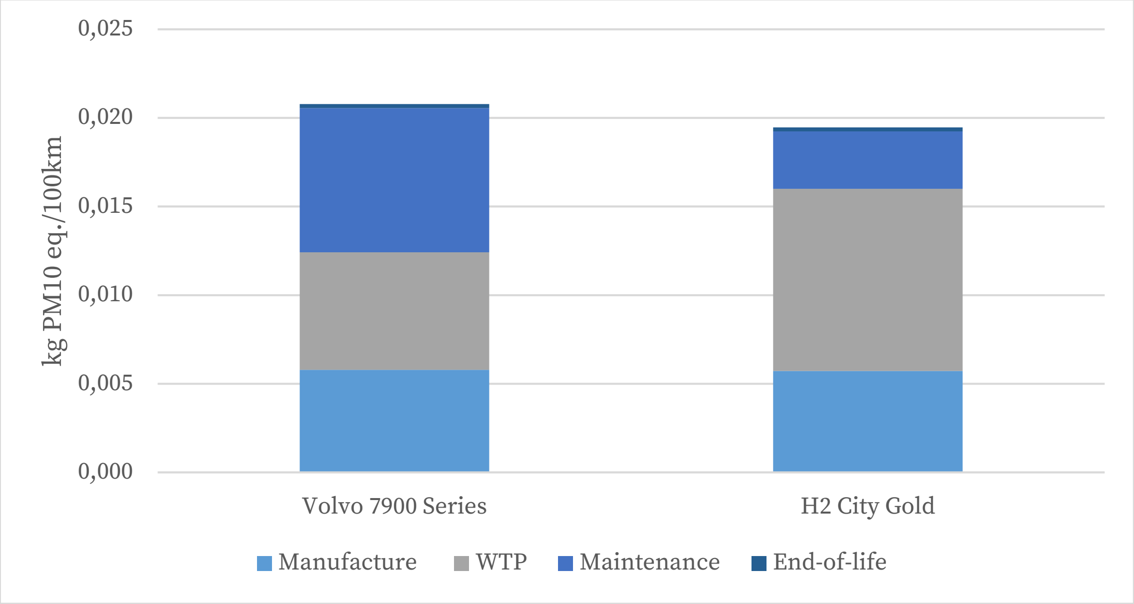


Figure 19. Differences between the two models for the PMFP (Source: own elaboration).

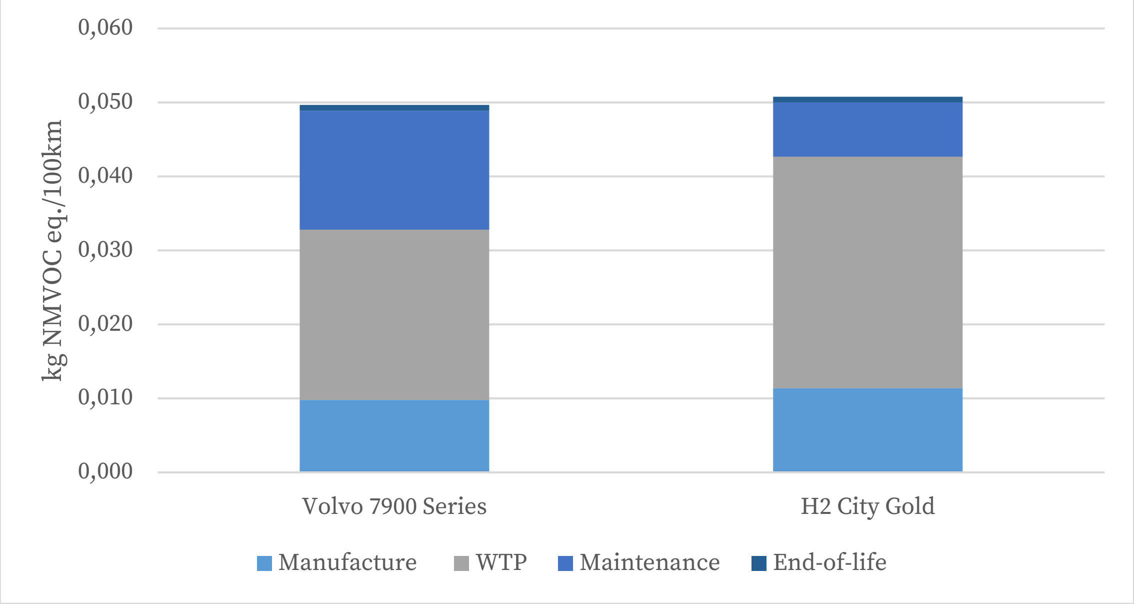


Figure 20. Differences between the two models for the OFP (Source: own elaboration).

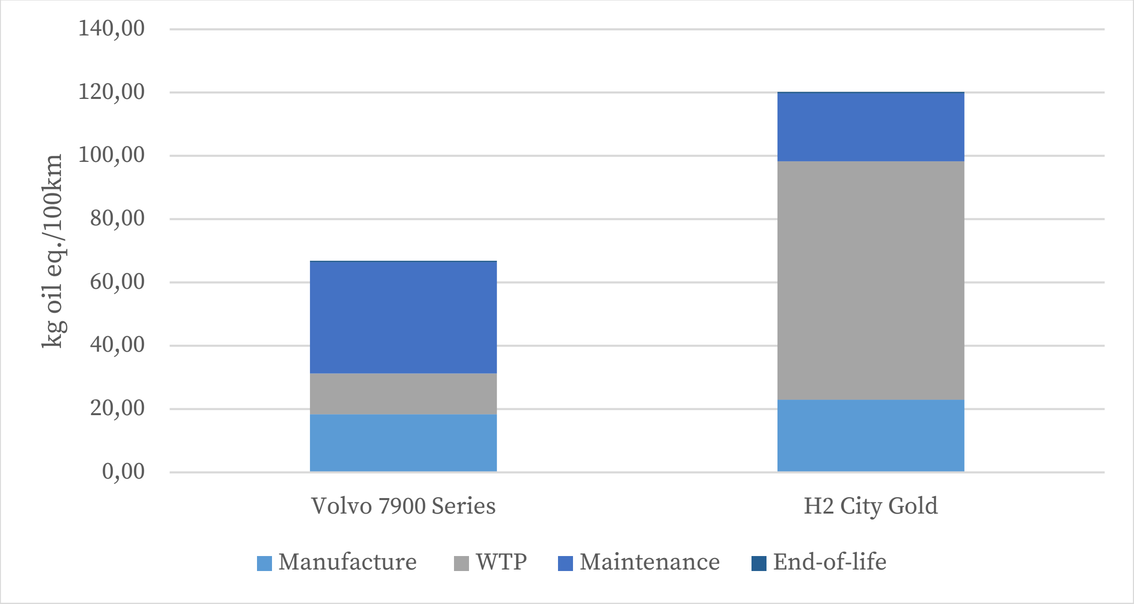


Figure 21. Differences between the two models for the FFDP (Source: own elaboration).

As it can be seen, the results are similar for Terrestrial acidification, the Particulate Matter Formation Potential and the Ozone Formation Potential. This is caused by the fact that both vehicles have similar components in general. It is important to remember that, due to lack of in deep information, the chassis, vehicle body, powertrain and transmission systems have the same weight. However, it can be seen that the maintenance and WTP phases in the Volvo bus equate the contribution of the WTP phase of the CaetanoBus.

As commented before, the main differences are observed to happen in the Global Warming Potential and Fossil Fuel Depletion, related to the production of the hydrogen and electricity.

It can be seen also in the following figures the differences between the results obtained for the different phases:

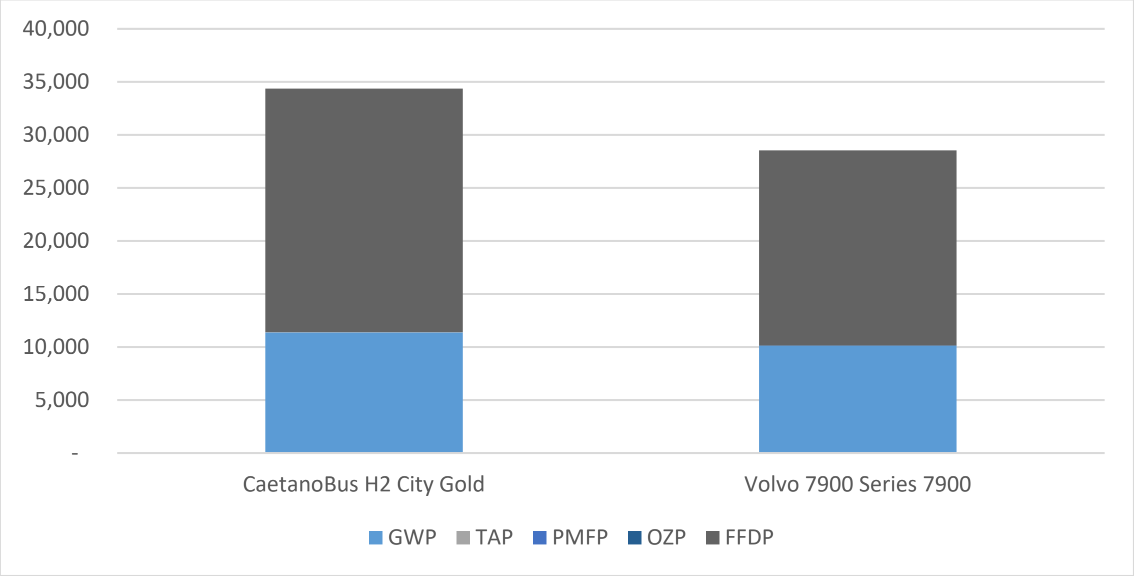


Figure 22. Manufacture phase results (Source: own elaboration).

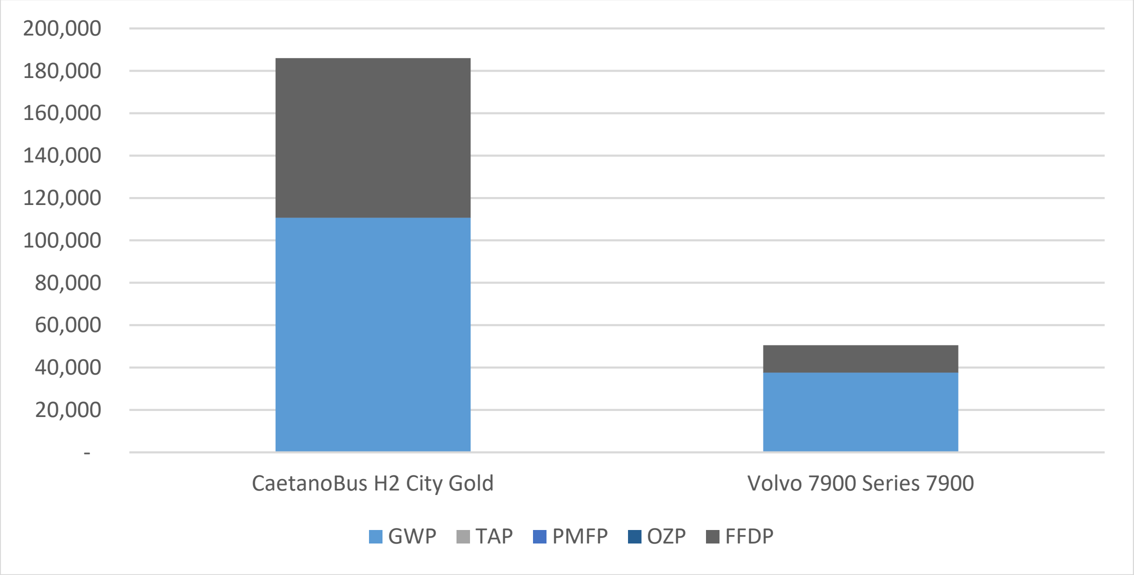


Figure 23. Well to pump phase results (Source: own elaboration).

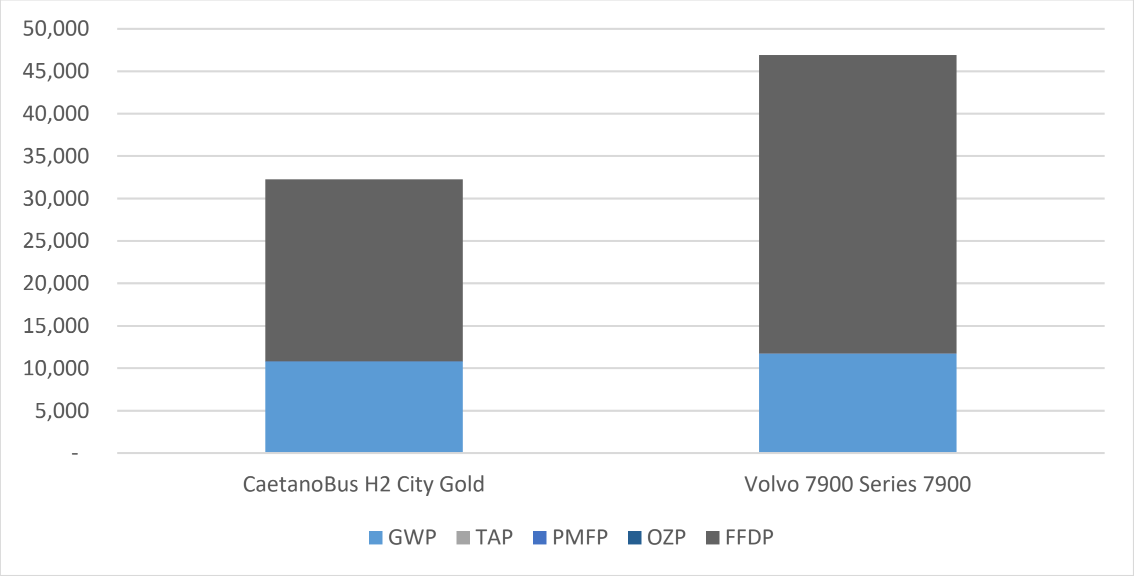


Figure 24. Maintenance phase results (Source: own elaboration).

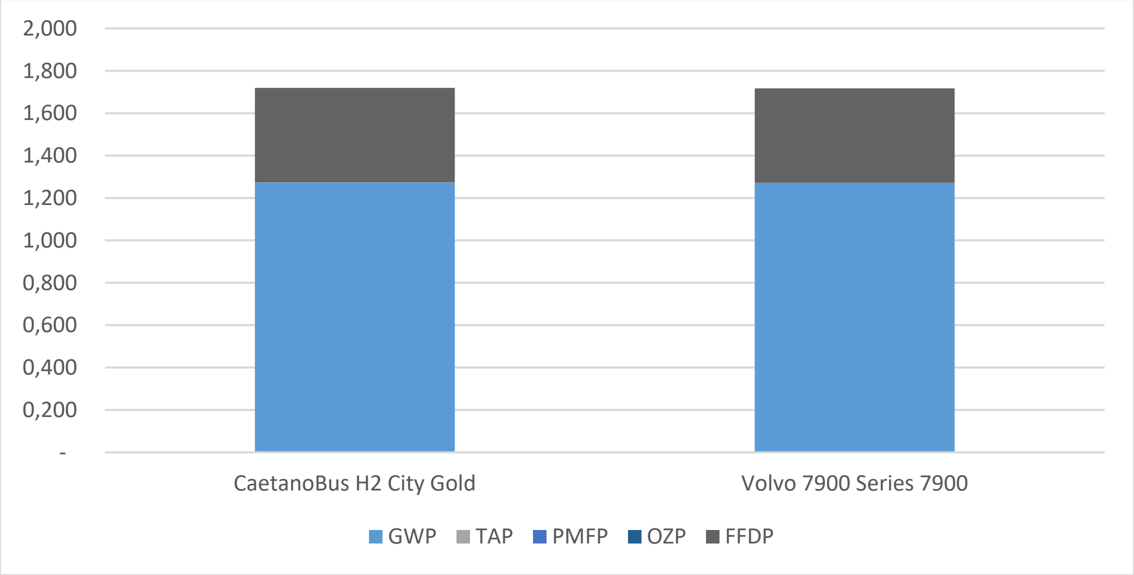


Figure 25. End-of-life phase results (Source: own elaboration).

As it can be observed, the results are quite similar in some of the phases. In manufacture phase, the difference lays in the batteries and fuel cell system materials and manufacture. It is determined then that the fuel cell manufacture is more harmful environmentally than the production of the batteries. However, these results must be considered with discretion, as it is required more in deep information about the amount and materials needed for both lithium-ion batteries and fuel cell systems in order to make a proper and robust statement. However, in despite of the difference in the impact of manufacture batteries it is observed that during the maintenance phase, the

CaetanoBus is less environmentally harmful than the Volvo 7900 Series. It is due to the fact that the batteries have to be replaced more than the fuel cell stack, which limits the environmental impact.

Nonetheless, the biggest difference observed is during the well to pup phase during the operational stage of the buses. The production of hydrogen is much more environmentally harmful than the electricity production. It is consistent, as the hydrogen is produced by natural gas produce an enormous amount of emission.

As a summary, in the following figure, it can be observed the overall aggregated potential environmental impacts results for both models considered in the study:

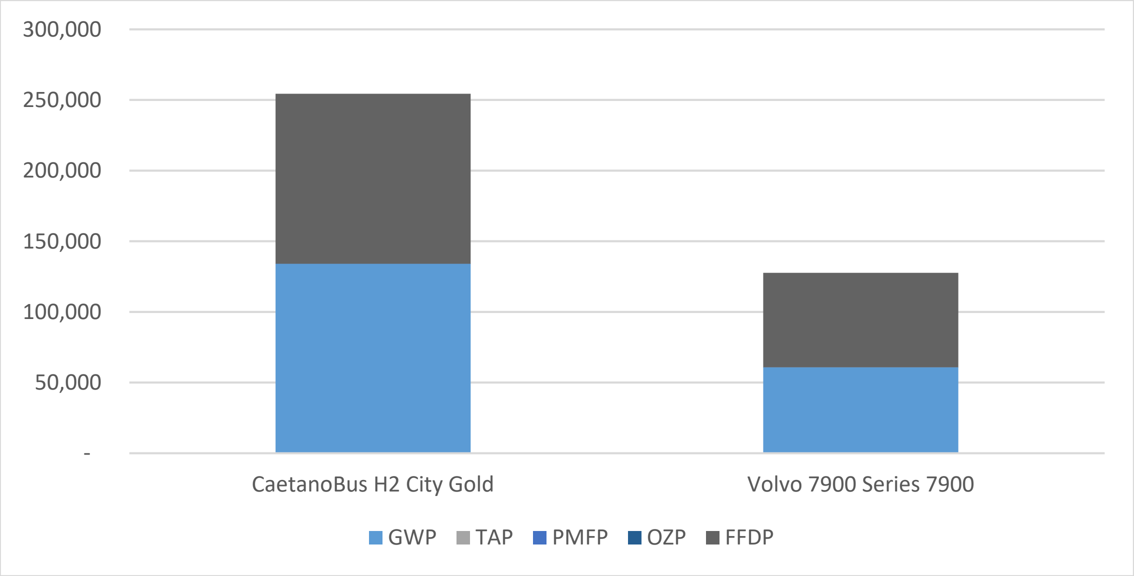


Figure 26. Overall results obtained for both models considered (Source: own elaboration).

In addition, the detailed emissions obtained for both models can be found in the following table:

Kg *x* eq./100km	CaetanoBus H2 City Gold	Volvo 7900 Series 7900
GWP	134.075	60.694
TAP	0.028	0.028
PMFP	0.019	0.021
OZP	0.051	0.050
FFDP	120.185	66.873

Table 26. Detailed results obtained for both models considered (Source: own elaboration).

6.2 Manufacture phase

The results regarding the manufacture process of both Volvo 7900 Series and the CaetanoBus H2 City Gold are showed in this section. The potential environmental impacts are presented by gathering the contributions for each component that conforms the vehicle. For hydrogen bus, the components are related to the Fuel cell pack (which includes the fuel cell on board storage the fuel cell balance of plant, the fuel cell management system and the fuel cell stack). This model also has lithium-ion batteries; its results can be seen in the so-called lithium-ion battery bill-of-materials label. These batteries are similar (in quantity of materials) than the once used for the Volvo bus, so the label name is the same in both cases (not the results). Besides, the chassis, vehicle body, traction motor, transmission system and vehicle fluids are also presented in the results and are similar in both vehicles model.

Firstly, the results for the H2 City Gold hydrogen bus are commented. As it can be seen the figure for each potential environmental impact there are different component that contributes the most. For instance, related to the global warming potential, the component that contribute more to the negative impacts are the chassis followed by the vehicle body. Respectively, the former has a 26 % of share and 2,908 kg CO_2 eq. /100km, and the latest has a share of 24% of the potential environmental impact, which is equivalent to 2,728 kg CO_2 eq. /100km. This is mainly due to the materials used to build up each component, that include steel, aluminium, plastic, rubber, among others, which produces a heavy environmental impact in terms of CO_2 equivalent emissions. The fuel cell balance of plant and the on-board storage have a significant contribution to the potential environmental impacts. Respectively, with 15% and 11% of the share of completely global warming potential. In terms of kg CO_2 eq. /100km the results are 1,65 kg CO_2 eq. /100km and 1,301 kg CO_2 eq. /100km, respectively. The components are also relevant to the contribution, as for instance the on board storage include galls and carbon fibber, which produces significant CO_2 emissions due to its compositions and manufacture. It is important to highlight that this results do not represent the specific impact. For instance, the weights of the chassis and the vehicle body are significantly bigger, being more than the 50% of the total weight of the vehicle but their potential impacts are not as bigger (which means a low specific impact). However, the BoP and the storage have less contribution over the total weight of the vehicle and their impacts are relevant, meaning that the specific impact is high.

Regarding other potential environmental impacts, on average, the components that contributes more are the former commented before, the chassis and the vehicle body. With an average of the 21% and 20% of the total impacts. A part from the balance of plant and the on board storage, the batteries and the fuel cell stack also contributes significantly. On average for all the categories, respectively contributes the 7% and the 10% of the total emissions.

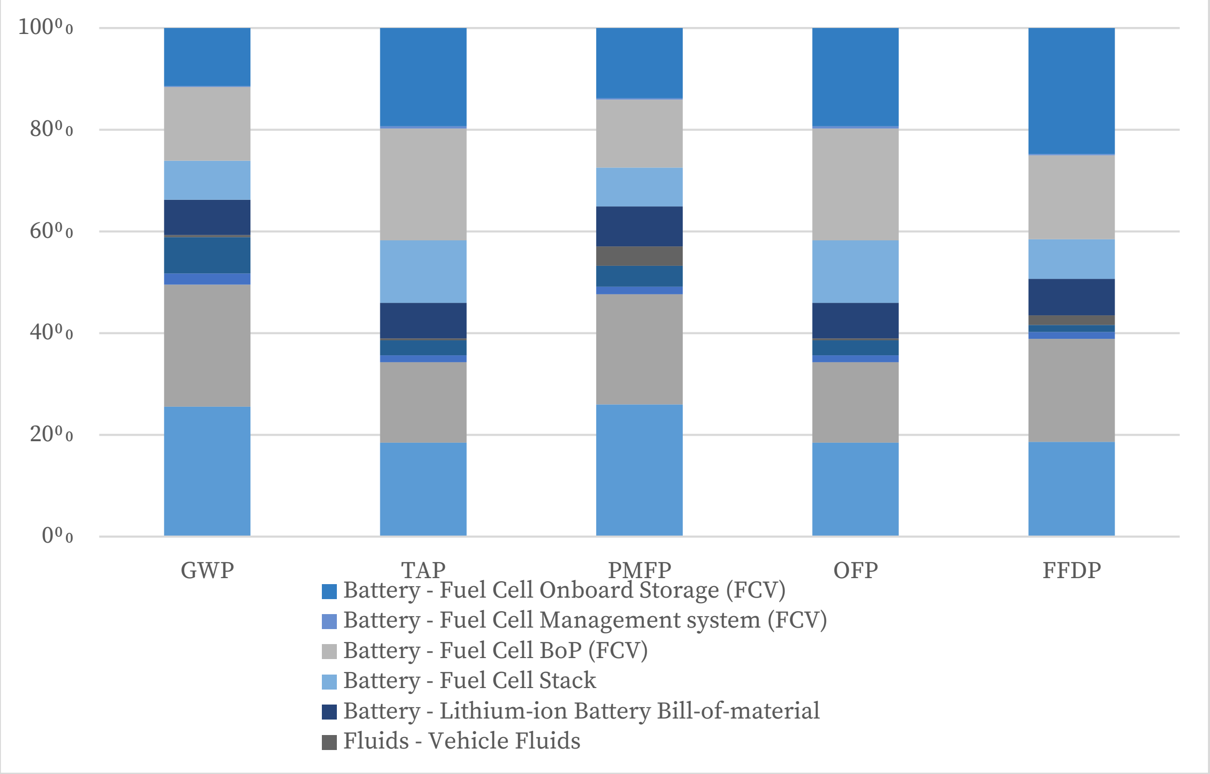


Figure 27. Manufacture results by share of contribution for each vehicle component (Source: own elaboration).

The detailed results of the manufacture phase for the H2 City Gold bus can be seen in the following table:

Kg x eq./100km	GWP		TAP		PMFP		OFP		FFDP	
Components - Chassis (w/o battery)	2.90	26%	0.0012	18%	0.0015	26%	0.0021	18%	4.280	19%

Kg x eq./100km	GWP		TAP		PMFP		OFP		FFDP	
Components - Vehicle Body	2.72	24%	0.0010	16%	0.0013	22%	0.0018	16%	4.65	20%
Components - Traction Motor (HEV, PHEV, EV, FCV)	0.25	2%	0.0001	1%	0.0001	2%	0.0002	1%	0.31	1%
Components - Transmission System/Gearbox	0.81	7%	0.0002	3%	0.0002	4%	0.0003	3%	0.32	1%
Fluids - Vehicle Fluids	0.04	0%	0.0000	0%	0.0002	4%	0.0000	0%	0.43	2%
Battery - Lithium-ion Battery Bill-of-material	0.78	7%	0.0004	7%	0.0005	8%	0.0008	7%	1.64	7%
Battery - Fuel Cell Stack	0.87	8%	0.0008	12%	0.0005	8%	0.0014	12%	1.79	8%
Battery - Fuel Cell BoP (FCV)	1.65	15%	0.0014	22%	0.0008	13%	0.0025	22%	3.79	17%
Battery - Fuel Cell Management system (FCV)	0.02	0%	0.0000	0%	0.0000	0%	0.0000	0%	0.06	0%
Battery - Fuel Cell On-board Storage (FCV)	1.30	11%	0.0012	19%	0.0008	14%	0.0022	19%	5.69	25%
Total	11.37		0.006		0.006		0.011		22.97	

Table 27. Detailed results for the manufacture phase of CaetanoBus (Source: own elaboration).

Regarding the Volvo electric, the model of the vehicle is simpler, as it does not require supplementary component to work properly the batteries (the hydrogen FC bus need the body of plant to ensure safety and a correct hydrogen supply to the fuel cell stack). Even though the simplicity of the model, the global result for the manufacture phase for the potential environmental impacts are similar to the hydrogen bus. For instance, 10,12 CO_2 eq. /100km of GWP for the electric bus and 11,37 CO_2 eq. /100km for the hydrogen bus or 108,39 4,7 kg oil eq. /100km for AEB and 22,97 4,7 kg oil eq. /100km for the FCB). The difference is slower if it is analysed the TAP, PMFP and OZP results (i.e. 0,0055 kg SO_2 eq. /100km for AEB and 0,006 kg SO_2 eq. /100km for FCB).

It can be seen clearly; which component contributes the most to the potential environmental impacts of the manufacture phases. As it stands out, the battery pack of the vehicle, add on average (between the shares of all the impact categories) a 42% of the total emission of this phase. That means, for instance the case of the global warming potential a total of 3,09 kg CO_2 eq. /100km or 0,0047 kg NMVOC eq. /100 km (which represent the 48 of the overall potential environmental impact). Similar to the batteries of the hydrogen bus, the batteries used for this vehicle unite components that are significantly harmful to the environment (i.e. NMC 622 cathode material, lithium, PVDF or N-MENTHYK-2-PYRROLIDONE).

Similar to CaetanoBus, chassis and vehicle body contribute significantly to the vehicle manufacture emissions. On average, the former has a share of 27% of the total emissions and the latest a 24%. Concretely, for the global warming potential, both vehicle components have similar emissions, being 2,9 kg CO_2 eq. /100km. Regarding to fossil fuel depletions the contribution is relevant as well (both components are made of metallurgic materials that requires high temperatures to be modelling and manufactured). The chassis consumes 5 kg oil eq. /100km and the vehicle body 4,7 kg oil eq. /100km.

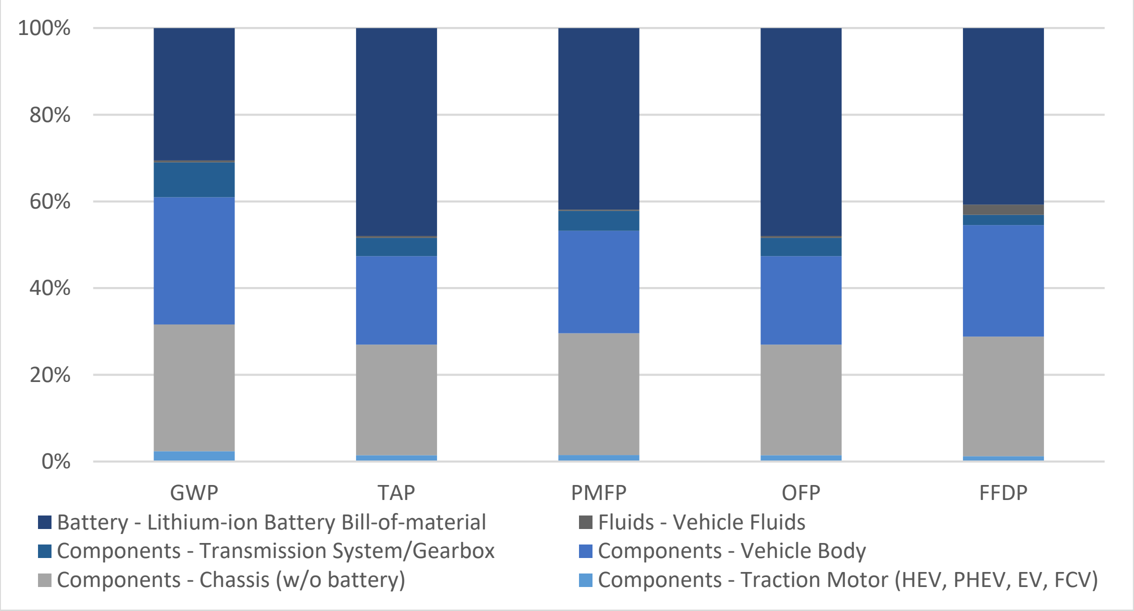


Figure 28. Manufacture results by share of contribution for each vehicle component (Source: own elaboration).

The detailed results of the manufacture phase for the Volvo 7900 Series bus can be seen in the following table:

Kg *x* eq./100km	GWP	%	TAP	%	PMFP	%	OFP	%	FFDP	%
Components - Traction Motor (HEV, PHEV, EV, FCV)	0.24	2	0.0001	1	0.0001	1	0.0001	1	0.22	1
Components - Chassis (w/o battery)	2.96	29	0.0014	26	0.0016	28	0.0025	26	5.07	28
Components - Vehicle Body	2.97	29	0.0011	20	0.0014	24	0.0020	20	4.74	26
Components - Transmission System/Gearbox	0.82	8	0.0002	4	0.0003	5	0.0004	4	0.43	2
Fluids - Vehicle Fluids	0.04	0	0.0000	0%	0.0000	0	0.0000	0	0.43	2
Battery - Lithium-ion Battery Bill-of-material	3.09	31	0.0026	48	0.0024	42	0.0047	48	7.49	41
Total	10.1		0.0055		0.0058		0.0098		18.4	

Table 28. Detailed results for the manufacture phase of the Volvo 7900 Series bus (Source: own elaboration).

6.3 Well to pump

In this section, the results for the well to pump phase are presented, which is included in the use phase (along with maintenance phase). These results consider the potential environmental impacts related to the production and distribution of the hydrogen used for the FC bus and the electricity generated to charge the batteries of the electric bus. In this case, the results are presented by the share each different pollutant emitted during the production of the fuel” and its contribution for each of the potential environmental impact.

It is important to highlight that during the use phase (well to pump plus maintenance phase) there are not exhaust emissions. As these emissions are related to the combustion of fossil fuels, i.e. diesel, natural gas among other. Therefore, the principal pollutant that contributes to the potential environmental impacts are CO_2, CH_2, CO, NO_x

and the particles PM10. It is shown also the related fossil fuel consumption during the production and distribution of hydrogen and electricity.

Firstly, the results for the hydrogen production are presented. Just to remind, the production of the hydrogen is mainly produced by means of natural gas. In fact, in Spain it is consumed approximately 500.000 t/year of hydrogen, 99% of the hydrogen produced being grey hydrogen from natural gas (Ministerio para la Trancissión Ecológica y el Reto Demográfico, 2020).

Therefore, it is consistent that this phase contributes the most regarding emissions. As the main source to generate the hydrogen consumed is natural gas. The environmental impact of the global warming potential is 110,632 kg CO_2 eq. /100km, which surpass other phases. The main pollutant that contribute to the potential impact is CO_2, with a total of 96,1 kg CO_2 eq. /100km (87%). Methane and CO have the similar contribution, around 7 kg CO_2 eq. /100km (approximately 8% and 6% respectively).

Regarding terrestrial acidification potential and ozone formation potential the main source that influence the results (due to the limitations of greet results) are NO_x. The former has an impact of 0,018 kg SO_2 eq. /100km and the latest an emission of 0,031 kg NMVOC eq./100km.

The particle matter formation potential, the NO_x has also relevance in terms of the total emissions, as it contributes 64% of the total. This means 0,007 kg PM10 eq. /100km. Besides, the generated particle matter PM10 contributes the rest, with a total of 0,004 kg PM10 eq. /100km (36%).

Finally, regarding the depletion of fossil fuels, the natural gas is the main source consumed by a 51%. This is equivalent to 38,4 kg oil eq. /100km. It is followed by the depletion of petroleum fuel, with a share of the 48%, equivalent a 36,4 kg oil eq. /100km. Coal fuel and methane are negligible in terms of contributions to potential environmental impacts.

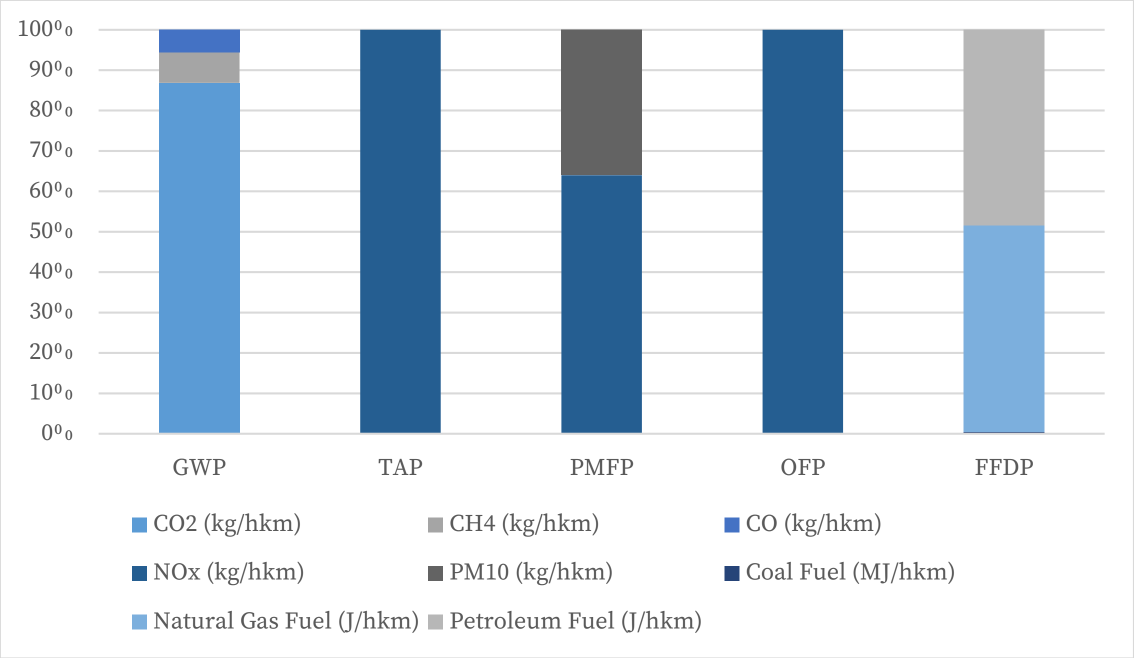


Figure 29. WTP impact results by share of contribution for each pollutant and fossil fuel consumption (Source: own elaboration).

The detailed results of the WTP phase for the H2 City Gold bus can be seen in the following table:

Kg *x* eq./100km	**GWP**	**%**	**TAP**	**%**	**PMFP**	**%**	**OFP**	**%**	**FFDP**	**%**
CO2	96.081	87								
CH4	8.372	8							0.195	
CO	6.179	6								
NOx	-		0.018	100	0.007	64	0.031	100		
PM10					0.004	36				
Coal Fuel									0.214	
Natural Gas Fuel									38.431	51
Petroleum Fuel									36.470	48
Total	110.632		0.018		0.010		0.031		75.310	

Table 29. Detailed impact results for the WTP phase (Source: own elaboration).

As commented before, with reference to the global warming potential the environmental impacts related to the production of the electricity are significantly smaller compared to the hydrogen production. In terms of values, electricity production is approximately 3 times lesser damaging for the environment and human health than the grey hydrogen (i.e. produce the hydrogen generates 110,6 kg CO_2 eq. /100km but generate the electricity 37,6 kg CO_2 eq. /100km). The Spaniard electricity mix is advantageous as an overall due to the relative elevated percentage of renewable energy used.

The same behaviour is observed for the fossil fuel depletion, where the electricity production only depleted 12,9 kg oil eq. /100km, mainly related to natural gas as well (8,28 kg oil eq. /100km) and petroleum fuel (3,65 kg oil eq. /100km), and the hydrogen production did 75,31 kg oil eq. /100km. Consequently, the FFDP also leads the electric option in a better situation to invest in, as the price of electricity is smaller than the hydrogen purchase price (commented in next chapters).

Regarding the terrestrial acidity potential and the ozone formation potential the impacts are related to NO_x. The former produces 0,013 kg SO_2 eq. /100km, which is less compared to the hydrogen production. The latest, the potential environmental potential related to OFP is equivalent to 0,023 kg NMVOC eq. /100km, also smaller than the production of the hydrogen.

The particle matter PM10 follows the same trend than the production of hydrogen. Being mostly affected by the contribution of NO_x. The emissions related to this are 0,0048 kg PM10 eq./ 100km, and the PM10 itself contributes 0,0018 kg PM10 eq./ 100km. Globally, again, the production of the electricity generates less impact in the human health than the production of the hydrogen.

These results can be observed in the following figure:

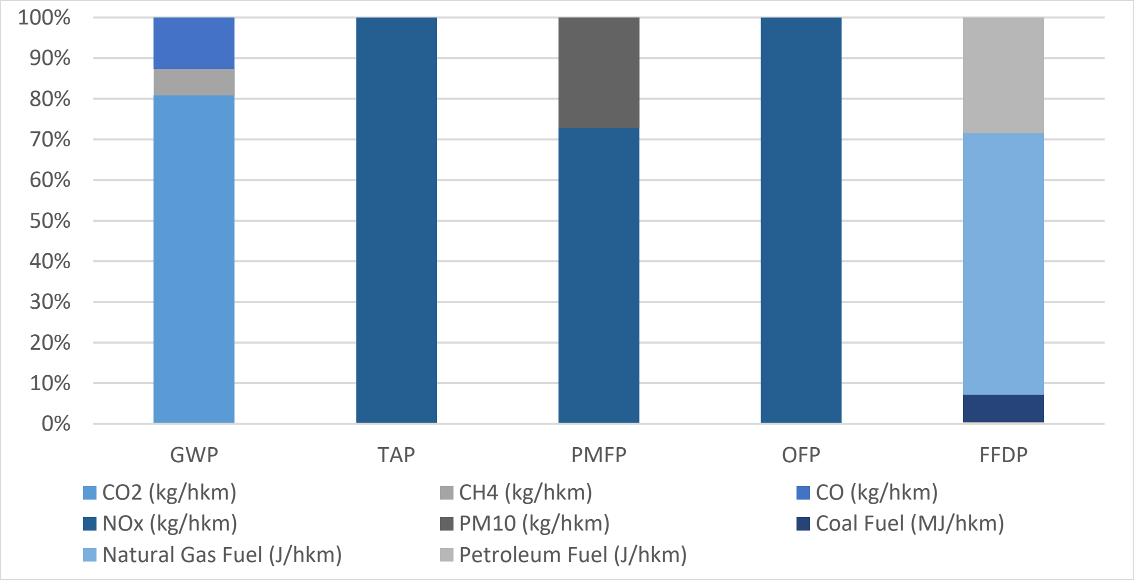


Figure 30. WTP impact results by share of contribution for each pollutant and fossil fuel consumption (Source: own elaboration).

The detailed results of the WTP phase for the Volvo 7900 series bus can be seen in the following table:

Kg *x* eq./100km	GWP	%	TAP	%	PMFP	%	OFP	%	FFDP	%
CO2	30.37	81								
CH4	2.46	7							0.06	
CO	4.75	13								
NOx			0.0129	100	0.0048	73	0.023	100		
PM10					0.0018	27				
Coal Fuel									0.88	7
Natural Gas Fuel									8.28	64
Petroleum Fuel									3.65	28
Total	37.59		0.0128		0.0066		0.023		12.87	

Table 30. Detailed impact results for the WTP phase (Source: own elaboration).

6.4 Maintenance phase

Maintenance potential environmental impacts potential are presented in this section. The results are shown by aggregating all the contributions of the different components replaced during the use phase. Therefore, the results include the replacements of the batteries packs, the fuel cell stack, the tires and the vehicle fluids. These replacements are related to the vehicle lifespan of 800.000 km driven and the number of times a replacement has to be done are commented in section 4.2.2.

The results for the H2 City Gold are commented first. As it can be observed, the lithium-ion battery replacement has the biggest impact related to the global warming potential. It has a total share of 38% of the total equivalent CO_2 generated during this phase. Which means 2,5 kg CO_2 eq. /100km. The replacement of fuel cell stack is also relevant as well, with 26% of share, which is 1,74 kg CO_2 eq. /100km. The total global warming potential of the hydrogen bus maintenance is 6,67 kg CO_2 eq. /100km.

In terms of terrestrial acidification potential, the trend chance totally. Both lion batteries and fuel cell stacks are the components with the biggest contributions, 33% and 38% respectively of the total amount of SO_2 eq. The fuel cell stack produces 0,0016 kg CO_2 eq. /100km due to its replacements and the batteries a total of 0,0014 kg CO_2 eq. /100km for the same reason. The same share is observed in the ozone formation potential, where the FCS produces 0,0028 kg NMVOC eq. /100km and the lithium-ion batteries 0,0024 kg NMVOC eq. /100km.

Regarding particle mater formation potential, the lithium-ion battery replacement contributes the most to the potential environmental impact. Its share is equivalent to 45%% and produces 0,0015 kg PM10 eq. /100km. It is followed again by the fuel cell stack replacement, which is equal to 0,0009 kg PM10 eq. /100km (28%).

Finally, vehicle fluids replacement contributes the most to the fossil fuel depletion potential due to the materials required to manufacture them (highly related to petroleum by-products). The depletion as a consequence of the vehicle fluid replacement is equal to 8,63 kg oil eq. /100km, which is a 40% of the total fossil fuel depletion potential. It is followed by lithium-ion battery and tire replacements, 4,94 kg oil eq. /100km and 4,33 kg oil eq. /100km respectively (which means a share of 23% and 20% of the total impact respectively).

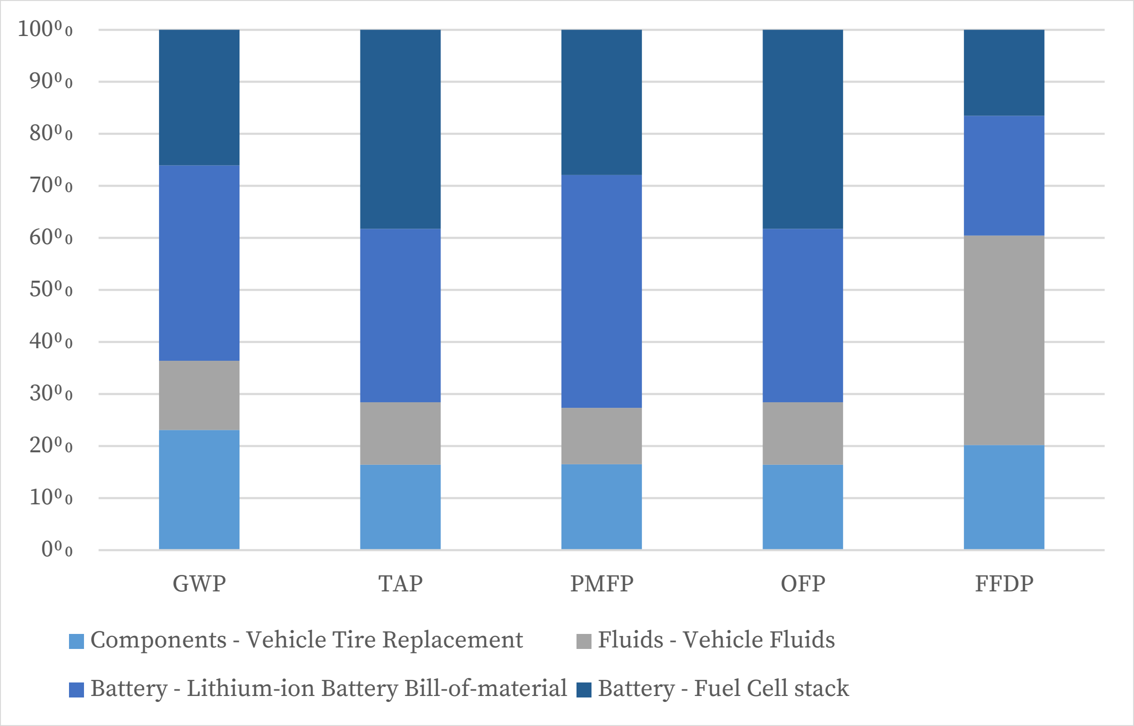


Figure 31. Maintenance impact results by share of contribution for each component replaced (Source: own elaboration).

The detailed results of the maintenance phase for the H2 City Gold bus can be seen in the following table:

Kg x eq./100km	GWP	%	TAP	%	PMFP	%	OFP	%	FFDP	%
Components - Vehicle Tire Replacement	1.54	23	0.0007	16	0.0005	16	0.0012	16	4.33	20
Fluids - Vehicle Fluids	0.89	13	0.0005	12	0.0004	11	0.0009	12	8.63	40
Battery - Lithium-ion Battery Bill-of-material	2.50	38	0.0014	33	0.0015	45	0.0024	33	4.94	23
Battery - Fuel Cell stack	1.74	26	0.0016	38	0.0009	28	0.0028	38	3.55	17
Total	6.67		0.0041		0.0032		0.0073		21.45	

Table 31. Detailed impact results for the maintenance phase (Source: own elaboration).

The Volvo 7900 Series case has same potential environmental impact results related to vehicle tire replacement and vehicle fluid replacements, as they are assumed to be equal and with the same maintenance route for both models.

Nonetheless, the lithium-ion battery replacement has the biggest contribution for the potential environmental impacts for the maintenance phase. As commented before, the electric buses require a bigger battery pack, which must be replaced 3 times. Therefore, manufacture and replace approximately more than one tone of batteries penalize the electric bus.

Regarding GWP the total emission generated by the batteries replacement is 9,28 kg CO_2 eq. /100km. For the terrestrial acidification potential, the impact is equivalent to 0,0078 kg SO_2 eq. /100km, similar to the emissions generated related to PMFP (0,0073 kg SO_2 eq. /100km). For the ozone formation potential, the related equivalent NMVOC emission are equivalent to 0,014 kg NMVOC eq. /100km. Finally, the fossil fuel depletion produced due to batteries replacement is equal to 22,2 kg oil eq. /100km.

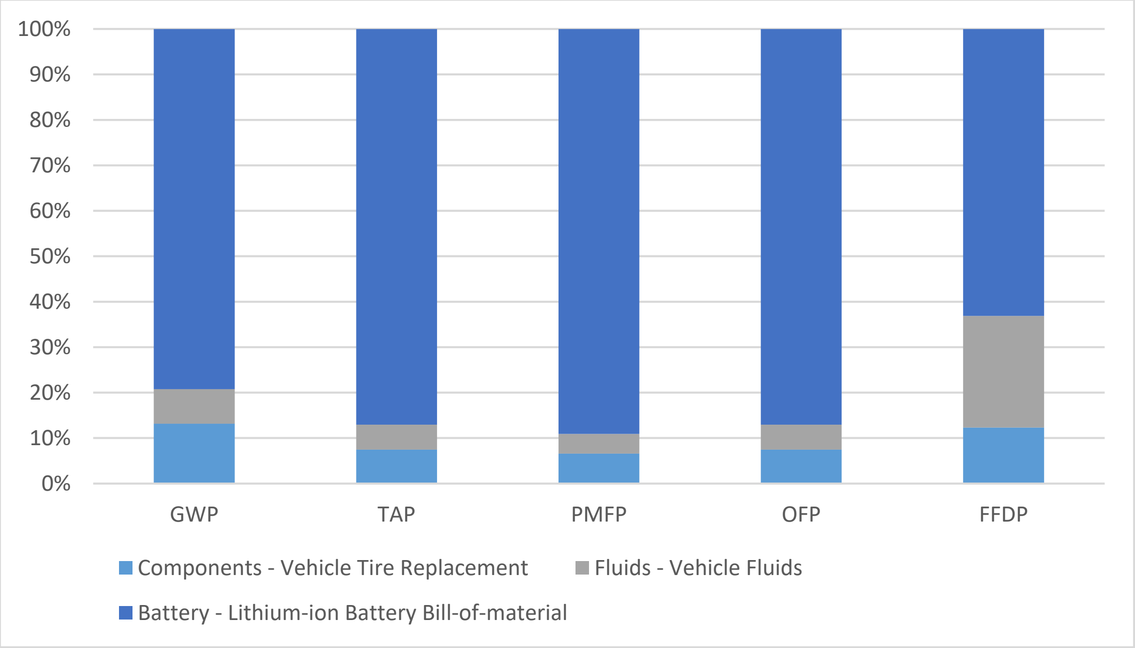


Figure 32 Maintenance impact results by share of contribution for each component replaced (Source: own elaboration).

The detailed results of the maintenance phase for the Volvo 7900 Series bus can be seen in the following table:

Kg *x* eq./100km	GWP	%	TAP	%	PMFP	%	OFP	%	FFDP	%
Components - Vehicle Tire Replacement	1.54	13	0.0007	7	0.0005	7	0.0012	7	4.33	12
Fluids - Vehicle Fluids	0.89	8	0.0005	5	0.0004	4	0.0009	5	8.63	25
Battery - Lithium-ion Battery Bill-of-material	9.28	79	0.0078	87	0.0073	89	0.0140	87	22.20	63
	11.71		0.0090		0.0081		0.0161		35.17	

Table 32. Detailed impact results for the maintenance phase (Source: own elaboration).

6.5 End-of-life

The environmental impacts related to the end-of-life phase of both H2 City Gold and 7900 Series models are presented in this section. The results include the disposal of different vehicle components. It is important to highlight that the recycling process are not include in the model as Greet does not possess datasets to analyse it properly (which would produce a reduction in the overall environmental impacts). Some EOL credits have been mentioned in section 6.1.

Therefore, the components taken into account in the model were the lithium-ion battery disposal, the fuel cell stack, the balance of plant, the hydrogen storage on board disposal, the FC management system, the chassis and vehicle body disposal, the electric motor and the transmission disposal.

As it can be observed, the results obtained are have the same emissions and fuel depletion for each component. This is due to lack of information of specific processes of disposal of each component. However, the emissions related to terrestrial acidification potential, particle mater formation potential and ozone formation potential can be neglected (the emissions are the order of E-4).

Regarding global warming potential, chassis, battery and body disposal (in that order) have the most contribution to the potential environmental impact (the share are respectively: 33%, 26% and 24%). Hence, the contribution for the chassis disposal is equivalent to 0,414 kg CO_2 eq. /100km, for the battery disposal is 0,33 kg CO_2 eq. /100km and for the body disposal is equal to 0,303 kg CO_2 eq. /100km.

Fossil fuel depletion have the same share than the GWP. Therefore, the contribution for the chassis disposal is equivalent to 0,145 kg oil eq. /100km, for the battery disposal is 0,117 kg oil eq. /100km and for the body disposal is equal to 0,106 kg oil eq. /100km.

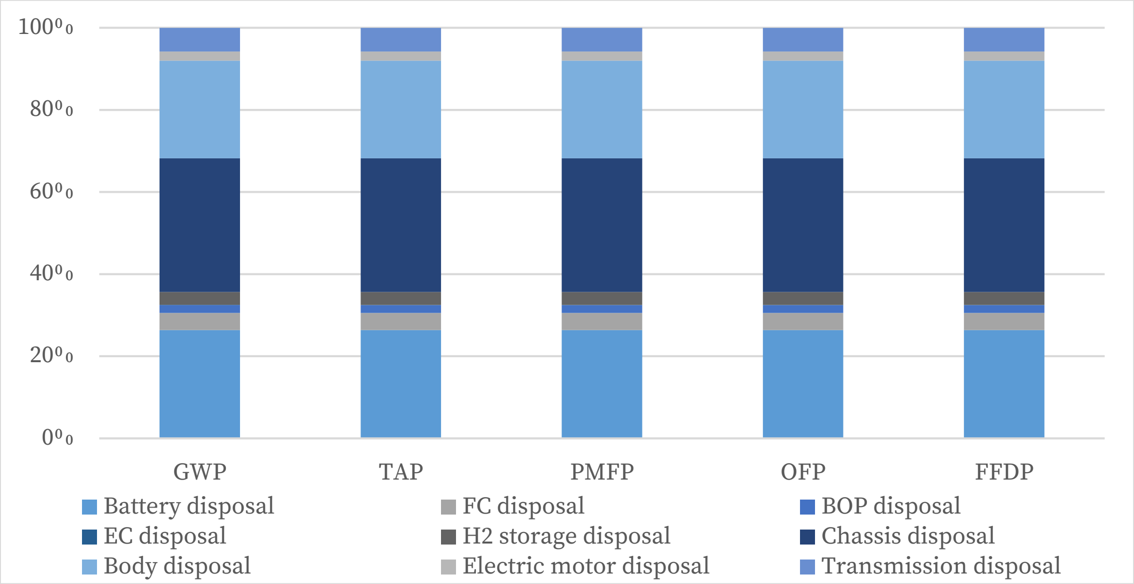


Figure 33. End-of-life impact results by share of contribution for each component disposed (Source: own elaboration).

The detailed results of the end-of-life phase for the H2 City Gold bus can be seen in the following table:

Kg *x* eq./100km	**GWP**	**%**	**TAP**	**%**	**PMFP**	**%**	**OFP**	**%**	**FFDP**	**%**
Battery disposal	0.336	26	0.000	26	0.000	26	0.000	26	0.117	26
FC disposal	0.053	4	0.000	4	0.000	4	0.000	4	0.019	4
BOP disposal	0.024	2	0.000	2	0.000	2	0.000	2	0.008	2
EC disposal	0.001	0	0.000	0	0.000	0	0.000	0	0.000	0
H2 storage disposal	0.040	3	0.000	3	0.000	3	0.000	3	0.014	3
Chassis disposal	0.414	33	0.000	33	0.000	33	0.000	33	0.145	33
Body disposal	0.303	24	0.000	24	0.000	24	0.000	24	0.106	24
Electric motor disposal	0.028	2	0.000	2	0.000	2	0.000	2	0.010	2
Transmission disposal	0.074	6	0.000	6	0.000	6	0.000	6	0.026	6
Total	1.273		0.000		0.000		0.001		0.446	

Figure 34. Detailed impact results for the end-of-life phase (Source: own elaboration).

Regarding the results for the Volvo 7900 Series, the potential environmental impact results are the same than the H2 bus for the chassis, vehicle body, the electric motor and the transmissions system disposal. The emissions related to terrestrial acidification potential, particle mater formation potential and ozone formation potential are also neglected.

It can be observed that the disposal of the all fuel cell system (including the batteries) are practically the same as the lithium-ion batteries of the AEB in terms of GWP. Both have a global warming potential equivalent to 1,27 kg CO_2 eq. /100km. The battery pack displacement contributes 0,452 kg CO_2 eq. /100km. Same happen with the fossil fuel depletion, where both have the same environmental impact 0,44 kg oil eq. /100km. The battery pack contributes 0,445 kg oil eq. /100km to the FFDP impact.

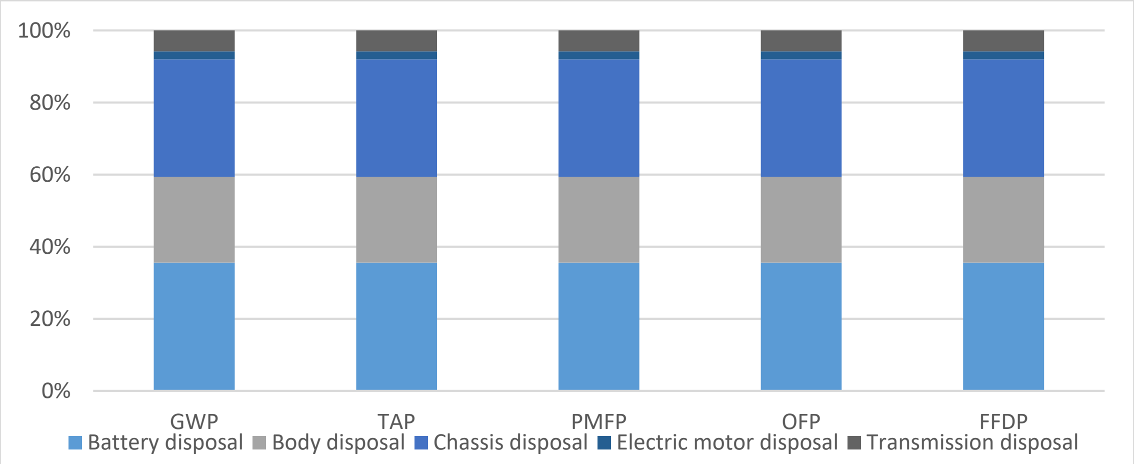


Figure 35. End-of-life impact results by share of contribution for each component disposed (Source: own elaboration).

The detailed results of the end-of-life phase for the Volvo 7900 Series bus can be seen in the following table:

Kg *x* eq./100km	GWP	%	TAP	%	PMFP	%	OFP	%	FFDP	%
Battery disposal	0.452	36	0.000	36	0.000	36	0.000	36	0.158	36
Body disposal	0.303	24	0.000	24	0.000	24	0.000	24	0.106	24
Chassis disposal	0.414	33	0.000	33	0.000	33	0.000	33	0.145	33
Electric motor disposal	0.028	2	0.000	2	0.000	2	0.000	2	0.010	2
Transmission disposal	0.074	6	0.000	6	0.000	6	0.000	6	0.026	6
Total	1.271		0.000		0.000		0.001		0.445	

Figure 36. Detailed impact results for the end-of-life phase (Source: own elaboration).

6.6 Cost of ownership

Apart from the environmental perspective and after analysed the impact related the bus models life cycle, it is important to compared these models from an economical point of view. Potential environmental impact should be strongly considered as a decision tool. However, it is widely known that cost of ownership is, at the end, the differential element to decide the investment related to the fleet models.

The total cost of ownership (TCO) is defined as *sum of all vehicle costs from its purchase phase, through usage, to its disposal"* (Szumska, et al., 2021) and it also includes the indirect cost purchase costs (Szumska, et al., 2021). It is commonly used to assess the use and possession cost of the vehicles used for transportation (i.e. transit buses) (Szumska, et al., 2021). According to the literature revised by Szumska, et al. (2021) the main cost categories considered in the studies about TCO are purchase cost, energy cost, repair, and maintenance costs.

In this case, the present study analyses two types of buses, an all-electric (AEB) bus and a fuel cell bus (FCB). Therefore, it is important to compare and analyse the total cost of ownership of both options in order to determine the most active option from an economical point of view. By doing this direct analysis and the related potential environmental impact results obtained by the Life Cycle Assessment, decision makers would be able to possess better understanding of both options and which one would fit better to achieve the objectives outlined by the governments.

Therefore, and following the suggestions by Szumska, et al. (2021), the categories analysed to stablish the total cost of ownership were the purchase cost, the energy consumption cost differenced in two parts, the energy infrastructure cost (the CAPEX required to build up the infrastructure) and the electricity or hydrogen purchase cost. Finally, the maintenance costs, also analysed in two subgroups, the infrastructure maintenance cost and the bus maintenance cost (which includes the cost of purchase the batteries and fuel cell replacements).

The presented costs are based on Transports Metropolitans de Barcelona (TMB) case study. Which is basically that all costs outlined during this part of the study are focused on characterised the related expense of each of the categories commented associated with TMB operations.

Firstly, the purchase cost of both models are presented. Regarding the CaetanoBus H2 City Gold model, its purchasing cost is equal to 800.000€. Which is the division of the related investment done by TMB of 6,4 M€ for the purchase of 8 CaetanoBus hydrogen models (Transports Metropolitans de Barcelona, 2021) (La Vanguardia, 2020). Nonetheless, the purchase cost of the Volvo 7900 Series was not available, as the cost related depends strongly on the operations, city and service operator. Consequently, the purchase cost of the Irizar 12m TMB electric buses was used. It is equivalent to 510.000 € without batteries (TMB, 2019). Therefore, the price of the lithium-ion batteries has to be determined. Some authors and specific related studies stated that the cost of the lithium-ion batteries are between 100-350 USD/kWh (IEA, 2018) (Mahmoudzadeh Andwari, et al., 2017) (Yong, et al., 2015). Hence, and based in Estrada, et al. (2022) it was assumed that the cost of batteries purchase was equal to 260 USD/kWh (at current exchange, it would be 260€/kWh). Hence, the cost of ownership of the electric option was equal to 595.800 €, considering the 330 kWh battery pack (Nordelof, et al., 2019). Consequently, to be comparable and proper to be analysed, the related cost of purchase is annualised per year of operation, taking into account the 12 years bus lifespan (Nordelof, et al., 2019). Finally, the annualised purchase cost for the CaetanoBus is 67.708 €/year (amortizations not considered) and 49.650 €/year for the Volvo 7900 Series.

The energy cost of the infrastructure related to the hydrogen production by natural gas is not considered, as the infrastructure is already constructed and because is considered the costs related to the construction of the on-site hydrogen production refuelling station in Barcelona. Which is the actual scenario that TMB is involved nowadays. The construction of the refuelling station had a cost of approximately 3,7 M€ (Europapress, 2021), which is also similar to the market values given by the Cost Analysis tool made by FCH (Fuel Cells and Hydrogen Joint Undertaking, 2020) (2,5 M€). The related infrastructure cost for the electric chargers are from TMB information (TMB, 2019) and is equivalent to 86.364 €/overnight-charger (a charger located in the depot of TMB for overnight charging). Therefore, to obtain the total cost of the infrastructure made by TMB, it was assumed that at depot there were 10 chargers destined directly for the bus line where the electric bus operates. This assumption is based in the study made by Estrada, et al. (2022) on V13 TMB bus line. Thus, the total cost of charging infrastructure is equal to 863.640 €. Finally, it was also assumed a infrastructure lifespan of 30 years (Estrada, et al., 2022), henceforth, the annualised cost for the hydrogen infrastructure is equal to 123.333 €/year and for the charging infrastructure is 28.788 €/year. It is important to remark that when the vehicle finishes its lifespan, the infrastructure will not be even at the middle of it, so some residual cost is included in the annualised cost.

The electricity cost and hydrogen cost is quite significant due to the fact that the cost of 1 kg hydrogen is much higher than the 1 kWh electric cost. Therefore, the cost of the kWh is assumed 0,06 €/kWh according to Estrada, et al. (2022). The consumption of the bus considered in the study was equal to 1,4 kWh/km, as a result, the cost per year due to the consumption of the bus is equal to 5.600 €/year. On the contrary, the hydrogen price depends on the production pathway (i.e. if the hydrogen is green, grey or blue). In this particular case, it was assumed that the hydrogen can be green or grey, with prices equivalent to 5,5 €/kg (Fuel Cell and Hydrogen 2 Joint Undertaking, 2020) (Hidrógeno Verde, 2021) and 1,5 €/kg (National Geographic Espana, 2022) respectively. As a result, the related price per year of hydrogen assuming 10,25 kg H2/100 km in the case of green hydrogen is equal to 37.583 €/year, and for the grey hydrogen is equal to 10.250 €/year (which is the one to be used as the base scenario considers grey hydrogen). It is also relevant to comment that likely TMB purchase cheaper the green hydrogen than the commercial price (Iberdrola, 2022) as it does with the kWh price

Henceforward, the maintenance cost related to the on-site hydrogen production infrastructure is equal to 151.000 €/year (Fuel Cells and Hydrogen Joint Undertaking, 2020). The related cost of maintenance infrastructure of chargers is assumed 19,6 €/charger-day (Estrada, et al., 2022). Therefore, the total cost of charging maintenance assuming 10 chargers at the depot is equal to 71.740 €/year.

The price of the replacement of the batteries and the fuel cell are annualised as well, as it play a significant cost. As commented in previous sections, the batteries were need to be replaced 3 times during the vehicle lifespan and the fuel cell stack twice. Again, assuming the purchase cost of the batteries are equal to 260 €/kWh and hence, the total cast of replacement annualised is 21.430 €/year. The cost of the fuel cell varies between 1.200 USD/kW and 455 USD/kW, based on (Lipman, et al., 2004) (Advanced Propulsion Centre UK , 2021). Thus, in this case, it is assumed that the fuel cell cost is equal to 1.200 €/kW. The fuel cell have 60 kW (CaetanoBus, 2019) and its annualised cost of replacement is 12.000 €/ year. The CaetanoBus has also two batteries of 44 kWh, which have to be replaced three times as well with the same price assumed for the electric bus option. The cost for replace the batteries are equal to 5.720 €/ year. Henceforward, the total cost of the replacements related to the Fuel Cell is 17.720 €/year.

Finally, the maintenance cost of the both models are considered. The maintenance cost of 12 meters electric bus operated by TMB is equal to 0,676 €/km. therefore, the total cost of maintenance assuming 300 of service per year (Estrada, et al., 2022) for this model is equal to 45.067 €/year. The annualised cost of maintenance of an hydrogen bus was obtained from the Cost Analysis tool made by FCH (Fuel Cells and Hydrogen Joint Undertaking, 2020) and it equal to 0,45 €/km. Consequently, the annualised maintenance cost for a hydrogen bus is 30.000 €/year.

In the following figure, it can be observed the total cost of ownership of both models divided by the different cost categories considered:

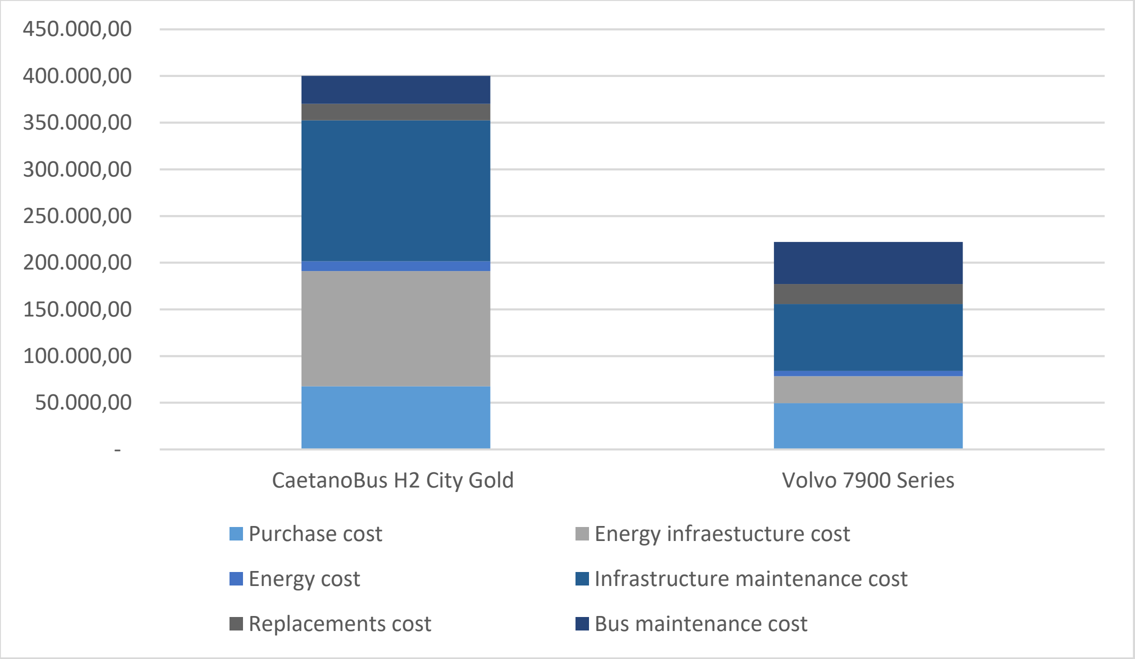


Figure 37. Total cost of ownership for the both models considered in the study (Source: own elaboration).

In addition, the detailed cost of each of the different categories can be observed in the following table in order to gather all the information for a better understanding:

€/year	CaetanoBus H2 City Gold	Volvo 7900 Series
Purchase cost	67,708.00	49,650.00
Energy infrastructure cost	123,333.00	28,788.00
Energy cost	10,250.00	5,600.00
Infrastructure maintenance cost	151,000.00	71,740.00
Replacements cost	17,720.00	21,430.00
Bus maintenance cost	30,000.00	45,067.00
Total cost of ownership	400,011.00	222,275.00

Table 33. Detailed information of the different cost considered in the TCO analysis (Source: own elaboration).

As it can be observed, the hydrogen option has double cost of ownership than the electric option. This due to firstly, the purchase cost is higher in the hydrogen case than the electric. Besides, of course the cost of infrastructure is considerably higher regarding the hydrogen production. The construction of new on-site production refuelling station requires an important investment to be operated, as it requires the construction of electricity supply, an electrolyser, a compression system, on-site storage tanks, refrigeration systems, dispensers and other complementary systems, such as H2 purifiers (Iberdrola, 2022). In addition, the safety issue of storage the hydrogen is relevant, so ensure a proper operation of the station is important. All these components complicate the operation and therefore the investment cost increase. On the contrary, the charger infrastructure is simpler and therefore the investment cost is restrained. Similar happens to the infrastructure maintenance cost, which is cheaper in the case of electricity as the facility does not have the same complexity than the hydrogen infrastructure. Which obviously possess more component to be maintained and again, to maintain a proper safety the maintenance has to be done more frequently. However, the maintenance cost of the buses is observed to be less significant on the hydrogen bus rather than the electric option.

Finally, the cost of acquire hydrogen is double the cost of electricity purchasing. The cost of the hydrogen is significantly higher than the electricity cost (1,5€/H2 kg and 0,06 €/kWh). However, the difference is not that notorious despite the huge difference of acquire price due to the major range and less consumption of the hydrogen bus (HyFLEET: CUTE, 2010). Actually, if the infrastructure construction investment and its maintenance cost is not taken into account, the difference between the total cost of ownership is not significant different between both models, only the 3% (the hydrogen cost would be 125.678 €/year and the electric bus would be 121.747 €/year).

7 Competitive analysis

It is well known that LCA are based on some degrees of assumptions and methodological definitions (Santesteban Garbe, 2020). Therefore, a sensitivity analysis is often required in order to analyse the assumptions made. However, in this case, the analysis is carried out focusing on the performance of the hydrogen bus against the electric bus. As it can be seen, the electric bus is, until now, the best option in environmental and economic terms. Therefore, the hydrogen bus offers some advantages (more range due to less consumption, flexibility, less maintenance cost) but its performance is limited otherwise.

For that reason, it was relevant to determine the achievements, developments and cost reductions that the hydrogen technology has to make in order to be competitive against the electric buses.

Other relevant cost that makes hydrogen vehicles to be less attractive is the infrastructure cost and its related maintenance cost or the purchase cots of the models. However, this costs are not related directly to the LCA carried out in this study. Therefore, they are not considered. It is relevant to consider, although, that the reduction of these cost will make the hydrogen option more competitive. Especially the infrastructure investment cost, which is the most difference cost against the electric infrastructure. However, these investments are not prone to be reduced unless governments support the hydrogen as a real tool for change. Besides, it can be considered that the for example the construction cost of the Barcelona's on-site hydrogen production plant would be used for more users than TMB. Therefore, the investment cost is not directly related to TMB only use and hence that will reduce the cost of ownership related to the infrastructure (same as the infrastructure maintenance cost).

7.1 Hydrogen production

The environmental perspective is considered relevant as a decision tool. Therefore, as it was observed, the production of the hydrogen penalised drastically the LCA of CaetanoBus during the operational phase (as it the phase with more differences between each other). Hence, the production of hydrogen has been modified in other to study the impacts of different strategies. The new scenarios assumed were, firstly, a big-scale electrolysis plant that uses the Spain electricity mix to proceed with the hydrogen production process and a distribution with tube trailers. The second scenario is an on-site refuelling station that produces its own hydrogen by electrolysis as well. The relevant aspect in this scenario, is that the electrolysis uses only renewable electricity mix (as explained in 4.1.2.2Compressed gaseous hydrogen production section).

In the following figure can be observed the aggregated well to pump (WTP) potential environmental impact of the different scenarios considered:

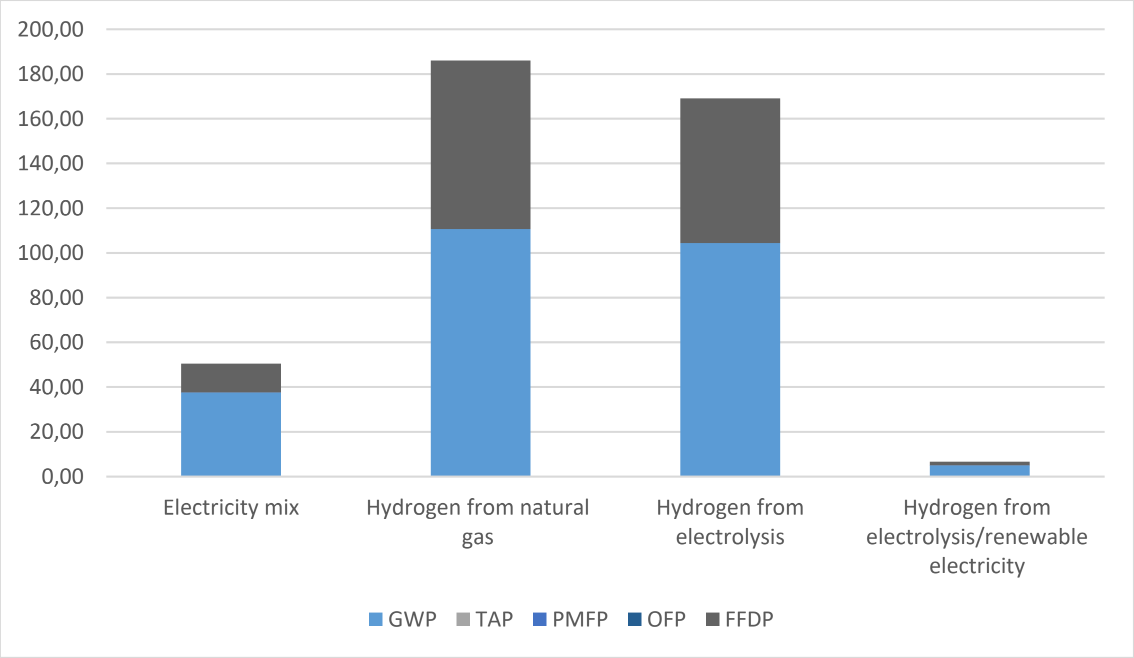


Figure 38. Aggregated WTP potential environmental impacts for the different scenarios considered (Source: own elaboration).

With the results obtained, it can be observed that the electrolysis production by means of electrolysis does not decrease significantly the environmental impacts. This is due to the huge amount of electricity required to the electrolysis to produce hydrogen. Electrolysis process divide the H_2O atoms in H_2 molecules and oxygen ones by applying electricity (Arjona, et al., 2008) and its efficiency is limited, over 77% (García Sánchez, et al., 2013). The global warming potential emission produced by the electrolysis in a large-scale plant is equal to 104,3 kg CO_2 eq. / 100km, which is only a reduction of 6% respect the hydrogen produced by natural gas (110,6 kg CO_2 eq. / 100km). However, the electrolysis production increases the terrestrial potential acidification by a 108%, as its generates more NO_x (0,036 kg SO_2 eq. / 100km respect the 0,0175 kg SO_2 eq. / 100km produced by natural gas hydrogen production). In fact, the electrolysis process also increase the emission related to PM formation potential and ozone formation potential compared to natural gas hydrogen production. Regarding PMFP, electrolysis produces a 83% more than natural gas (0,0188 kg PM10 eq./100 km compared to 0,0103 kg PM10 eq./100 km compared) and 108% more OFP, 0,065 kg NMVOC eq./100 km compared to0,0313 kg NMVOC eq./100 km emitted by natural gas hydrogen production. Nonetheless, this process reduces the fossil fuel depletion by a 14% with respect to base scenario. Which is 64,4 kg of kg oil eq./100 km against 72,31 kg oil eq./100 km. In conclusion, the electrolysis to produce hydrogen in a large-scale plant in not worthy in terms of environmental impacts, even though it reduces the GWP, it is more harmful for human and fauna health as it produces more NO_x and PM10 particles.

However, as it can be seen in the figure, the on-site hydrogen production increases the overall environmental attractiveness of the hydrogen bus as it decreases drastically the potential environmental impacts related to the well to pump phase. By using renewable energy for the electrolysis for produce, hydrogen it is reduced the emissions of pollutant and particles related to other fossil-based energy. The observed emissions are related to the compression and other process that were assumed to use the Spain electricity mix. The reduction of all the emission are around the 93/ on average. For example, the GWP is reduced 95%, going from the 110,6 kg CO_2 eq. / 100km for the base scenario to the 4,99 kg CO_2 eq. / 100km for the on-site hydrogen production. Compared to the base hydrogen production scenario, TAP is reduced by 90%, being its related emission equal to 0,0017 kg SO_2 eq. / 100km. PMFP is reduced to 0,0009 kg PM10 eq./100 km (91% decrease). The OFP is set to 0,0030 kg NMVOC eq./100 km (reduction of 90%). And finally, the FFD potential is reduced until 1,71 kg oil eq./100 km, with a related decrease of 98%.

Henceforth, the use of green hydrogen (which is produced by electrolysis with electricity from renewable energies (Ministerio para la Trancissión Ecológica y el Reto Demográfico, 2020)) would increase the environmental attractiveness of the hydrogen bus. Therefore, it will the hydrogen bus more suitable to achieve the environmental objectives outlined by the governments and will help to reduce furthermore the emissions related to transportation activities. As the most disadvantage related to the ownership of the hydrogen bus was the production of the hydrogen, if renewable energy is used the overall environmental impact will be reduced, even more than the compared electric bus. This can be seen in the following figure:

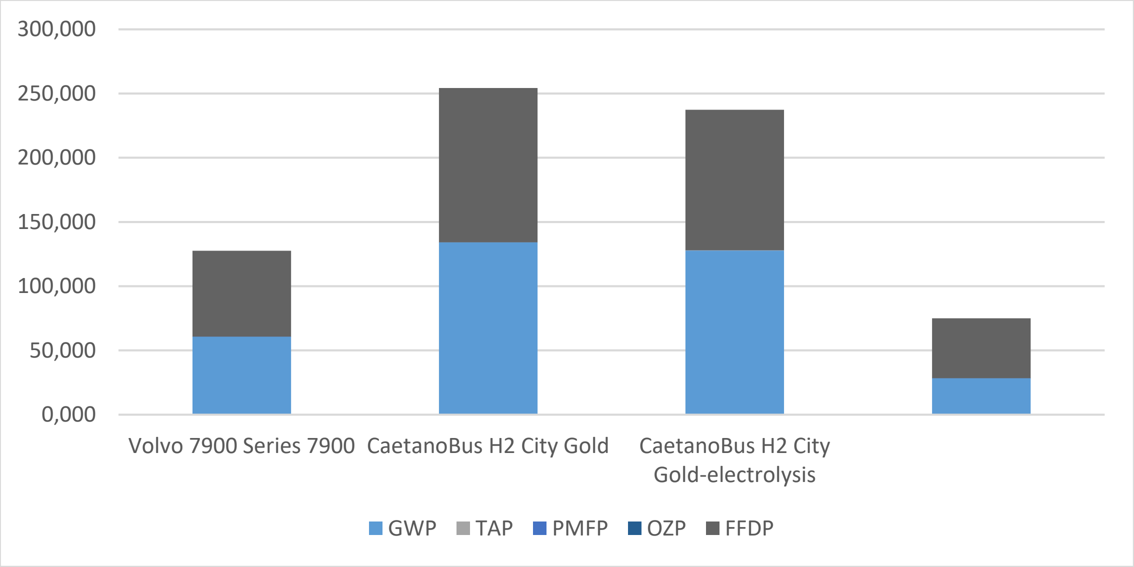


Figure 39. Overall results obtained for the scenarios considered (Source: own elaboration).

Detailed information about the results obtained for the different scenarios can be seen in the following table:

Kg *x* eq./100km	**Volvo 7900 Series 7900**	**CaetanoBus H2 City Gold**	**CaetanoBus H2 City Gold-electrolysis**	
GWP	60.694	134.075	127.777	28.434
TAP	0.028	0.028	0.047	0.013
PMFP	0.021	0.019	0.028	0.010
OZP	0.050	0.051	0.084	0.022
FFDP	66.873	120.185	109.478	46.583

Figure 40. Detailed overall results obtained for the different scenario assessed (Source: own elaboration).

7.2 Price hydrogen purchase and consumption rate

Other relevant detriment related to the hydrogen total cost of ownership is the price purchase of the hydrogen. Which is drastically expensive than the electricity price. As a reminder, the price of grey hydrogen is equal to 1,5 €/kg and the price per kWh in Spain is assumed 0,06 €/kWh (Estrada, et al., 2022). As a consequence, the consumption rate of the vehicle is also related to the cost of hydrogen acquisition, not the price itself but the total energy cost. Because when higher consumption of H2 kg per100 km of the vehicle the higher the receipt of hydrogen. For that reason, both analysis was carried together, as one influences the other. The consumption analysis is also analysed on the emissions generated during the well to pump phase, in order to compare them with the potential environmental impacts related to the electricity well to pump phase. Consequently, a reduction of consumption of hydrogen will reduce also the potential environmental impacts.

Therefore, the analysis is carried out in two scenarios related to the price of hydrogen and thus, the production process related. The first scenario is based on grey hydrogen prices and production processes, the second scenario is conducted by assuming a production of hydrogen on-site by electrolysis, and hence, the related green hydrogen price. As commented in 6.6Cost of ownership, the price of green hydrogen is equivalent to 5,5 €/kg (Fuel Cell and Hydrogen 2 Joint Undertaking, 2020) (Hidrógeno Verde, 2021) and the related price of grey hydrogen is 1,5 €/kg (National Geographic Espana, 2022).

Firstly, the consumption analysis has been carried out assuming the price of grey hydrogen. That means the production of the hydrogen is natural gas base. Therefore, in this part of the analysis, the analysis was made in order to determine the maximum consumption rate of the hydrogen to match the same potential environmental emissions than the electric option and therefore be competitive enough. Besides, with the price of the grey hydrogen, the consumptions rate evaluated are sufficient competitive to increase the attractiveness of the hydrogen bus.

The assumptions were two apart from the base scenario. Firstly, a consumption 6 kg H2/100km was used. This consumption is based on CaetanoBus' information about bus model characteristics (CaetanoBus, 2019). Secondly, the consumption of consumption 6 kg H2/100km was reduced the same rate founded in Davide, et al (2022). This paper concluded a consumption reduction of 41% of the model used in the analysis with respect CUTE project foundlings, presented in 2008. Therefore, the second consumption assumed for the analysis was 3,54 kg H2/100km.

The results obtained can be found in the following figure:

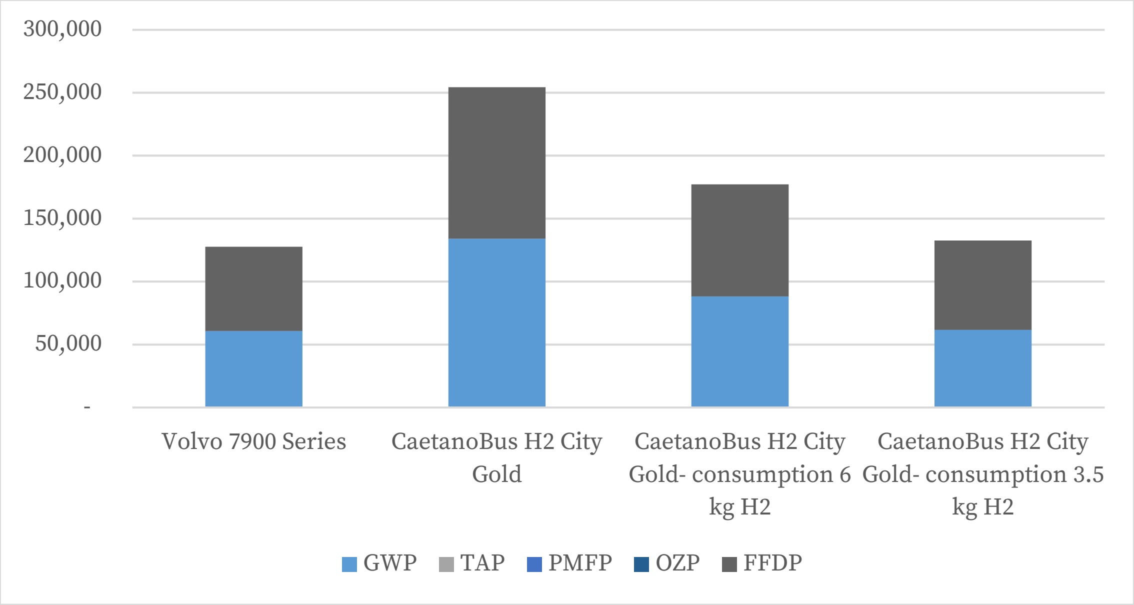


Figure 41. Results obtained for different consumptions rate (Source: own elaboration).

As it can be seen, for the consumption rate sated by the bus manufacturer, the overall potential environmental impacts are not reduced enough to be as competitive as Volvo 7900 Series electric bus. The results are equivalent to an aggregated 88,9 kg of pollutants eq. /100km, but the electric bus has an emissions of 66,8 kg of pollutants eq. /100km, which is a positive difference of the 33%. However, if considers the price of the grey hydrogen static (1,5 €/kg H2) the energy purchase cost is starting to be competitive, as it would be 6.000 €/year for the hydrogen and 5.400 €/year, a difference of 7% that is not too much meaningful. Nonetheless, the environmental impact is still significant.

The second consumption assumption matches the electric environmental impacts. The total potential pollutants emissions are 70,8 kg pollutants eq. /100km, which is only 6% higher than the related electric environmental impacts. This means a reduction, respect the base scenario of 41%. Which would clearly put the hydrogen bus competitive respect the electric bus with respect the environmental impacts. Besides, if the acquisition is considered as well as 1,5 €/ kg H2, the reduction respect the electricity overall purchase would be significantly. The total price due to hydrogen overall purchase would be equal to 3.540 €/year, which is 37% less with respect the electricity facture. Therefore, if the technology is developed enough to reduce the consumption rate to 3,54 kg H2/100km or even more, the hydrogen option would be a serious option against the electric bus (which of course will have some technological improvements as well) in both energy cost purchasing and environmental impacts perspective.

A more detailed vision of the results obtained can be seen in the following table:

Kg *x* eq./100 km	**GWP**	**TAP**	**PMFP**	**OZP**	**FFDP**	**Energy cost**
Volvo 7900 Series	60.69	0.03	0.02	0.05	66.87	5,600.00
CaetanoBus H2 City Gold	134.07	0.03	0.02	0.05	120.19	10,250.00
CaetanoBus H2 City Gold- consumption 6 kg H2	88.18	0.02	0.02	0.04	88.94	6,000.00
CaetanoBus H2 City Gold- consumption 3.5 kg H2	61.63	0.02	0.01	0.03	70.87	3,540.00

Table 34. Detailed results of the different consumption rates analysed (Source: own elaboration).

As it was commented in previous chapters, the production on-site production with electricity from renewable energies have significant lower emission respect the electric bus. For this scenario, therefore, the part related to the consumption and its potential environmental impacts was not that important. It was assumed the same two cases commented before. In this specific case, the relevant parameter was related the purchase cost of energy. For green hydrogen, the price of 1 kg is equal to 5,5 €/kg H2 (Fuel Cell and Hydrogen 2 Joint Undertaking, 2020) (Hidrógeno Verde, 2021) which make it not competitive against the electricity cost.

For that reason, and based on the consumption rates used previously (10,25 kg H2/100 km, 6 kg H2/100 km and 3,54 kg H2/100 km), a solver analysis was carried out in order to determine the maximum prices that green hydrogen should has in order to be competitive against the electric bus. The actual cost of the energy purchase with the consumption assumed to be 10,25 kg H2/100 km is equal to 37.583 €/year. This is a difference of 571 % higher than the facture related to electricity.

The results obtained can be found in the following figure:

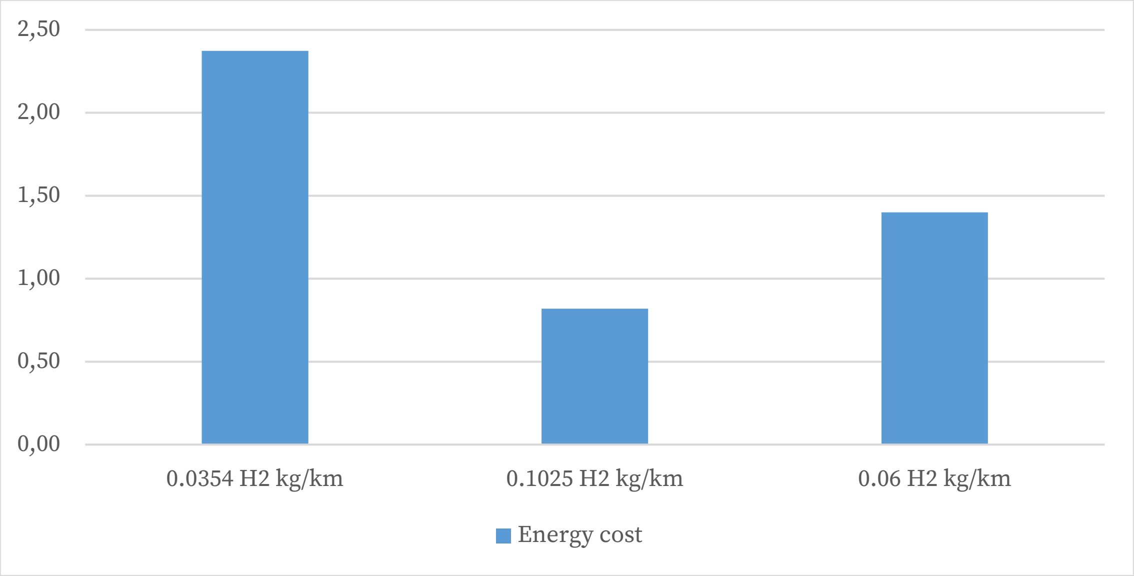


Figure 42. Energy cost require equating the electricity energy cost (Source: own elaboration).

As it can be observed, for the base consumption rate, the price of the green hydrogen must be reduced until 0,82 €/kg to be equal than the electric energy purchase cost. This reduction is significantly higher, which is decrease of 85% the actual green hydrogen cost. However, achieve such reduction is complicated to happen within the next decade (IRENA, 2020). Regarding to the consumption rate assumptions, the hydrogen cost reduction is less significant, being both over the euro per kilogram. For the6 kg H2/100 km scenario, the hydrogen cost should be 1,4 €/kg H2 to be as competitive as the electric bus option. This is a relevant achievement, as it would be more or less equal to the grey hydrogen price (1,5 €/kg H2), which will significantly boost hydrogen technology and its related developments. Therefore, with Barcelona's on-site hydrogen production, with the consumption rates stated by CaetanoBus and a reduction of 75% of the price, the hydrogen bus would be more attractive than the electric option. As it would experience a significant reduction in environmental impacts and the energy, cost would be the same as the electric bus. Making the CaetanoBus option more attractive. Finally, if the consumption rate is reduced until 3,57 kg/100km, the competitive price should be 2,37 €/kg H2. Which means a reduction of the 57% of the actual price.

7.3 Lithium-ion battery lifespan

As it was observed, electric vehicle option is quite a powerful option against the hydrogen bus. However, the battery pack used by AEB plays relevant role within the total vehicle cost of ownership and the environmental impacts related maintenance. The related lifespan is a significant aspect to be considered, as depending on it the replacement costs and the emissions generated can vary considerably. In the base scenario, the lifespan of the lithium-ion battery pack used by the Volvo 7900 Series was assumed to be 220.000 km or an equivalence of 3,3 years (considering the vehicle lifespan of 800.000 km and 12 years of service) based on (Garc´a Sánchez, et al., 2013). Therefore, in this part of the study, three different scenarios were assumed regarding lifespan in order to analyse its environmental impacts compared to Volvo and CaetanoBus' base scenario (this last one has less environmental and economic impact than Volvo maintenance). The three scenarios were: first, an scenario were battery lifespan was equal to 2,5 years (approximately the lifespan commented in (Davide, et al., 2022)); the second scenario is assumed that the lifespan is equal to 5 years; and the third, the lifespan of the batteries were assumed to be 7 years.

In the following figure can be observed the aggregated maintenance phase potential environmental impact of the different scenarios considered:

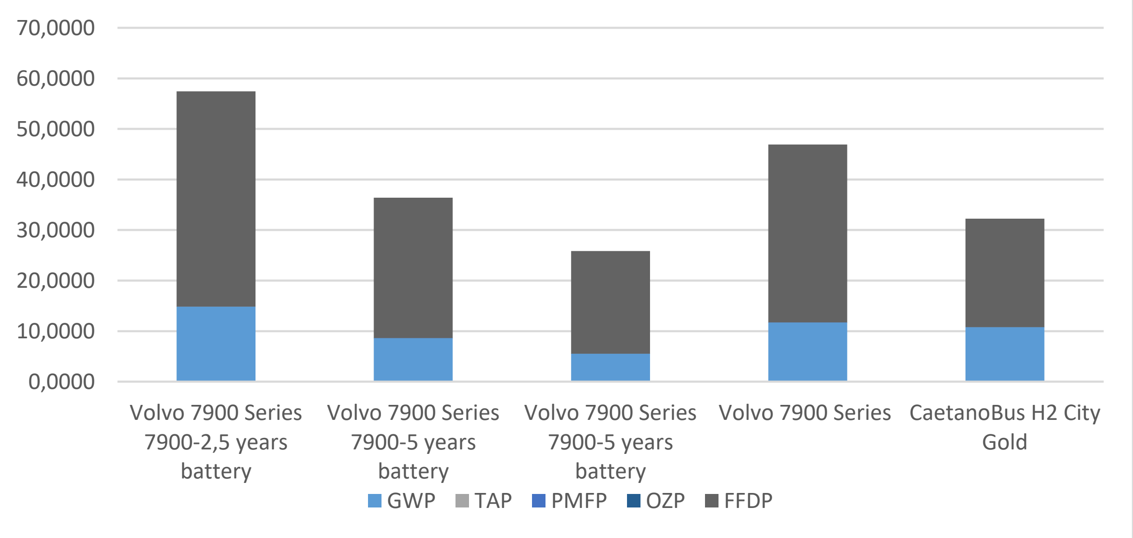


Figure 43. Aggregated maintenance phase potential environmental impact of the different scenarios considered (Source: own elaboration).

As it can be observed in the figure above, two of the scenario are more harmful than the hydrogen option maintenance. As it is obvious, the scenario was the lifespan of batteries is decreased, the emissions increase significantly. The global warming potential of this scenario is equal to 14,8 kg Co_2 eq./ 100km, which is 27% higher than the base scenario considered (11,7 kg CO_2 eq./ 100km) and 37% higher than the CaetanoBus emissions (10,8 kg Co_2 eq./ 100km). the bigger differences observed compared to the hydrogen option are related to terrestrial acidification, PM formation potential and ozone formation, when de differences are respectively: 182 %(0,011 kg SO_2 eq./ 100km for the electric option), 225% (0,01 kg PM10 eq./ 100km for the electric option) and 182% (0,02 kg NMVOC eq./ 100km the electric bus). As observed in other sections, the maintenance phase of the batteries has higher environmental impacts than the production of the fuel cell. Therefore, if the lifespan is considered as the obtained after real operation process, the impact increase significantly. In other words, most of the times, the lifespan stated by the manufacturers does not match with the real lifespan obtained while the vehicle is in operation, which is often smaller and depends on the charging strategy used (TMB, 2019). This produces negative impacts regarding the planning of replacements and maintenance programs as well as an increase of the cost related. Besides, as it can be observed, these problems make the electric option to be less competitive than the hydrogen model, which requires less replacements and have less potential environmental impacts in this phase.

Nonetheless, technological developments can change the trend and produce more durable and adaptive batteries. For this reason, the other two scenarios were assumed. The 5 years' life span is less environmental impacts than the base scenario. On average, the 5 years' lifespan scenario is 27% less harmful than the Volvo's base scenario. However, it still has 35% more harmful environmental impacts than the CaetanoBus' scenario. However, the GWP of this scenario is equal to 8,62 kg CO_2 eq./ 100km, smaller than the observed CaetanoBus emissions (which are 10,8 kg CO_2 eq./ 100km, 20% higher). In addition, the difference of emissions related to TAP, PMFP and OFP are higher than the CaetanoBus on an elevated rate than other categories (approximately 62% higher on average, when the other impacts are about 7% higher than the hydrogen option. Even though the reduction of GWP, this scenario is not competitive against the CaetanoBus, the difference in overall emission is equal to 13%.

Regarding the final scenario, were the lifespan is considered to last 7 years, the trend is different. In this case, the competitiveness of the electric bus is higher than the hydrogen model. This is clary because the lifespan is higher enough to only replace the battery pack once. Therefore, the emissions related this phase are reduced considerably, more if considered the electric base scenario. On average, the reduction rated compared to the hydrogen option is 14%. It is important to highlight that this scenario is able to reduce 49% the global warming potential emissions (5,5 kg CO_2 eq./ 100km compared to 10,8 kg CO_2 eq./ 100km of the hydrogen model). However, the other categories do not have the same reduction rate, which is on average only 5% less than the hydrogen model. Nonetheless, the OFP is still higher than the CaetanoBus bus, but only 1% higher (0,007 kg NMVOC eq./ 100km compared to 0,0073 kg NMVOC eq./ 100km).

A more detailed vision of the results obtained can be seen in the following table:

Kg *x* eq./100 km	GWP	TAP	PMFP	OZP	FFDP
Volvo 7900 Series 7900-2,5 years battery	14.8154	0.0116	0.0105	0.0207	42.5921
Volvo 7900 Series 7900-5 years battery	8.6278	0.0064	0.0057	0.0114	27.7438
Volvo 7900 Series 7900-5 years battery	5.5229	0.0037	0.0033	0.0067	20.3197
Volvo 7900 Series	11.7103	0.0090	0.0081	0.0161	35.1680
CaetanoBus H2 City Gold	10.7933	0.0041	0.0032	0.0073	21.4521

Table 35. Detailed results of the different scenarios analysed (Source: own elaboration).

In addition, the related maintenance cost is also analysed for the different scenarios assumed. The cost of the batteries were assumed to be the same than in section 6.6 Cost of ownership (which was assumed to be 260 €/kWh (Estrada, et al., 2022)). The trends follow the same pattern than the emissions analyses.

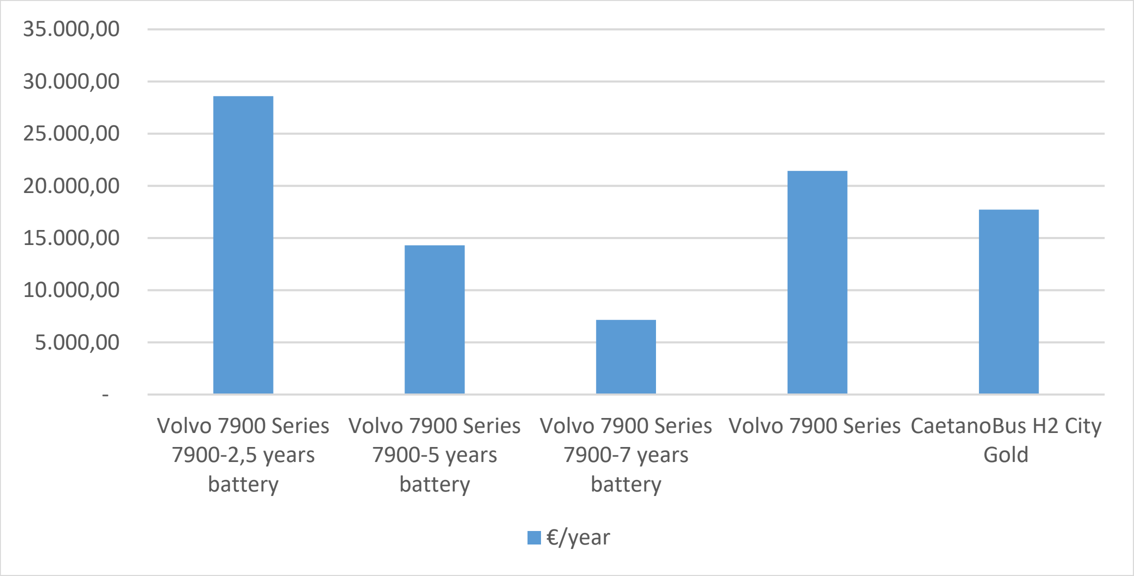


Figure 44. Replacement cost of the different scenarios analysed (Source: own elaboration).

It can be seen that the 2,5 years' lifespan battery is not economically competitive against neither the Volvo base scenario and the hydrogen model case. Its maintenance cost is equal to 28.600 €/year, which is 33% higher than the electric base scenario and 61% compared to the hydrogen scenario. The 5 years' lifespan battery is more economical competitive than the hydrogen model, as the batteries must only to be replaced twice during the vehicle operation lifespan. Its maintenance cost is equal to 14.300 €/year, -33% smaller than the Volvo base scenario and 19% smaller cost than the hydrogen model. Finally, the 7 years' lifespan battery is by far the most competitive option, both environmentally and economically. The replacement cost of this scenario is 7,150 €/year, which is 67% smaller than the Volvo base scenario and 60% less compared to the hydrogen model.

A detailed vision of the results obtained can be seen in the following table:

Scenario	€/year	Difference with Volvo	Difference with Caetano
Volvo 7900 Series 7900-2,5 years battery	28,600.00	33%	61%
Volvo 7900 Series 7900-5 years battery	14,300.00	-33%	-19%
Volvo 7900 Series 7900-7 years battery	7,150.00	-67%	-60%
Volvo 7900 Series	21,430.00		

Scenario	€/year	Difference with Volvo	Difference with Caetano
CaetanoBus H2 City Gold	17,720.00		

Table 36. Detailed results of the different scenarios analysed (Source: own elaboration).

However, it is important to highlight that the technological development required to decrease considerably the environmental impacts due to the replacement schedules needs more time to be implemented. However, governments, the industry and the society are choosing the electric mobility as the tool of the decarbonisation of the mobility (European Comission, 2020). Therefore, the development period should be considerably reduced as huge amount of money is invested in electro-mobility solutions and infrastructure (Pollák, et al., 2021).

7.4 Electricity purchase cost

The prices considered in the base scenarios were assumed to be like that before the Ukrainian war, which brought uncertainty to the economy and the society. Besides, the electric sector have suffered relevant changes during the past years in Spain (National Geographic Espana, 2021). The price of the kWh is now related to the price of the gas, which has produced an enormous increase in the electricity purchase cost (La Moncloa, 2022). In addition, this analysis is also significant regarding the charging strategy, as depending of the hour of the day the strategy used change for a super-faster charger o to a conventional one. Therefore, when trying to choose the best option, the price of the electricity must be a variable to take into account. Besides, this will also affect the battery lifespan, affecting the replacement schedule and also the battery pack capacity installed in the bus. Opportunity charging related to super-faster chargers uses battery packs approximately of 150 kW and over-night charging uses approximately 330 kW battery packs, as once needs to hold all day operation while the other just have to hold the line length.

Therefore, in this study, the electricity price was assumed to be 0,06 €/kWh based on (Estrada, et al., 2022) study. However, in order to observe the impact of the electricity price in the competitiveness of the electrical model against the hydrogen model, four prices scenarios were assumed and compared to the results obtained when analysing the hydrogen cost (7.2 Price hydrogen purchase and consumption rate). The prices were divided in four time periods: the first between 00-07 h, second between 07-13 h, third between 13-18 h, and the fourth between18-24h. Prices were taken from the *Sistema de información del operador del Sistema"* which is developed by the Red Eléctrica (Red Eléctrica, 2022). The assumed reference day was the 9th of May 2022. The prices can be observed in the following figure:

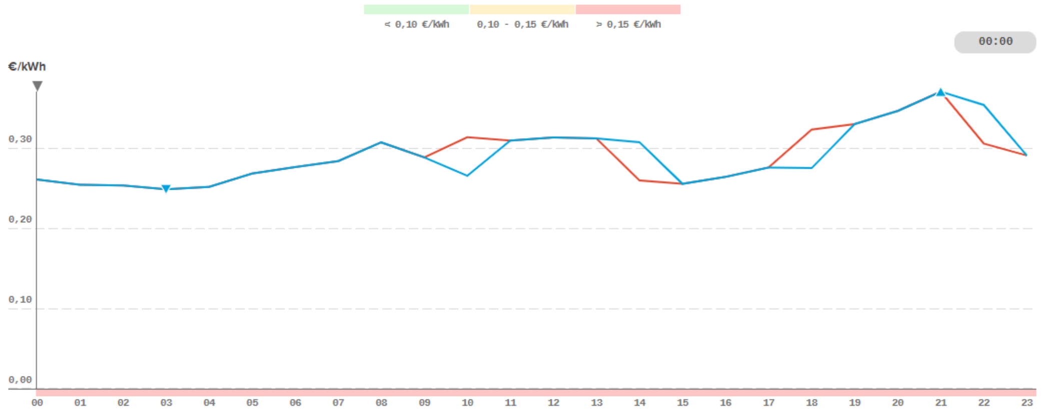


Figure 45. Electricity price depending of the hour of the day (Source: (Red Eléctrica, 2022)).

Therefore, the prices used were the following, which are the average price observed in the above figure:

Time period	Price €/kWh
00-07 h	0.25
07-13 h	0.31
13-18 h	Therefore, assuming the same consumption rate tha0.28
18-24 h	0.35

Table 37. Electricity price assumed depending on the time period (Source: own elaboration based on (Red Eléctrica, 2022)).

Therefore, assuming the same consumption rate than the Volvo's base scenario (1,4 kWh/1km) the annualised cost of electricity purchase of the different scenarios were calculated. In addition, the results were compared against the hydrogen cost (both green -5,5 €/kg H2- and grey -1,5 €/kg H2- hydrogen). The results obtained were as follows:

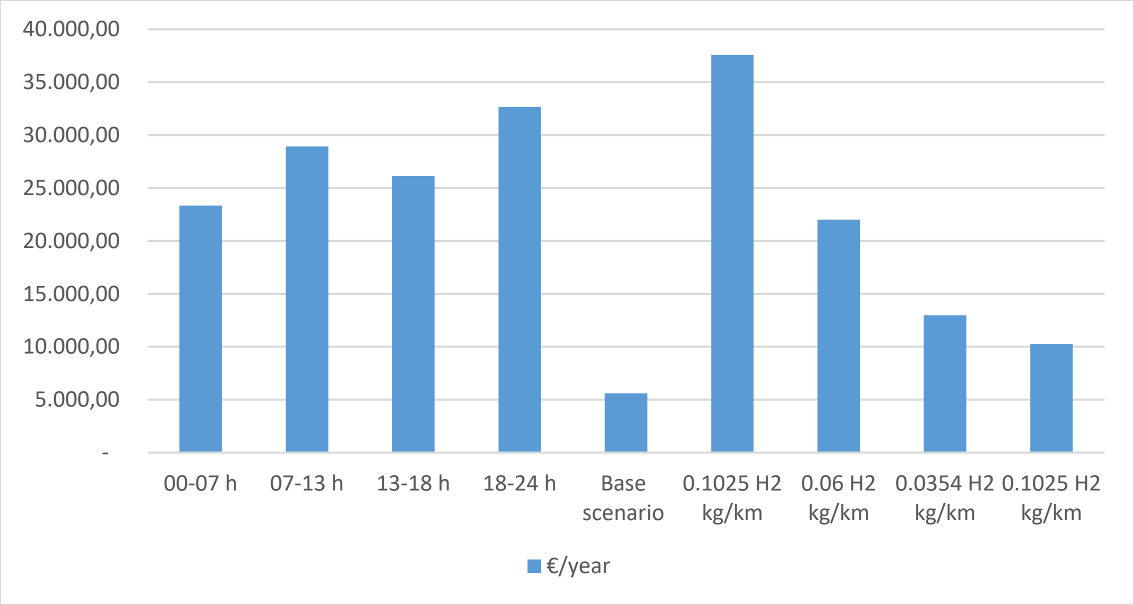


Figure 46. Annualised electricity cost of the different scenarios considered (Source: own elaboration).

As it can be seen, the differences against the base scenario are significantly higher. On average, the average cost of electricity purchase is 396% higher than the electricity price base scenario. The night period, which is between 00h and 07 h would cost 23.333 €/year, 317% higher than the base scenario. The following time period, from 07h to 13h is even more expensive, increasing the annual cost until 28.933 €/year (417% higher than the base scenario). This is the second more expensive period. The third time period, from 13 h to 18h, is cheaper than the previous period, but higher than the fist. The annualised cost regarding the third period is 26.133 €/year (367% higher than the base scenario). Finally, the las scenario is the most expensive, which goes from 18h to 24h, approximately 483% higher than the base scenario. This means an annualised electricity cost of 32.667 €/year.

Therefore, with the increase of the electricity prices, the attractiveness of the electric model is decreased, as this aspect was an advantage before (the hydrogen prices was considerable higher than the electric price). To observe these, the annualised cost of the different electricity prince scenario was compared to the green and grey hydrogen prices. In addition, the consumption rates of the hydrogen model were also modified for the green hydrogen price. Firstly, the new electricity prices were compared to the hydrogen price base scenario.

All of the new electricity prices scenarios are higher than the grey hydrogen purchase cost. On average, the electricity prices are 171% higher than the hydrogen base scenario (which is equal to 10.250 €/year). However, it is important to highlight that the electricity production is considerable less harmful than the grey hydrogen production, thing that could compensate the higher purchase prices. However, if comparing the green hydrogen scenario with any of the new electricity scenario, the former is still expensive. The prices of the time period between 18-24 h has the highest purchase cost, but the green hydrogen scenario is 15% higher (32.667 €/year against 37.583 €/year). Nonetheless, the higher difference observed was between the green hydrogen scenario and the time period between 00h and 07h with a difference of 38%. Therefore, the competitiveness of the green hydrogen is increasing due to the change in electricity prices. If these continues the scalable trend observed during the last year (Red Eléctrica, 2022), the electricity model would not be the best option if the green hydrogen prices remains the same (also it has less potential environmental impacts). Besides, as the price of the electricity depends on the supply and the demand, while more vehicles and elements are electric the price can increase even more (National Geographic Espana, 2021). However, it cannot be neglected that the green hydrogen requires electricity from renewable energy to be produced and some increase of prices can be experienced as well. However, the relative can be reduced if on-site hydrogen production uses its own electricity production by photovoltaic panels (Iberdrola, 2021).

In addition, if compering the consumption rates reduction scenarios of the hydrogen model with the electricity prices, the disadvantage of the latest is increasing. If the consumption rate of the hydrogen bus were reduced to 6 kg H2/100km, the purchasing cost of green hydrogen (maintaining the actual hydrogen price) would be cheaper than any of the new electricity prices scenarios. The related cost would be 22.000 €/year for green hydrogen and 23.333 €/year for the cheapest new electricity price scenario.

In the following table, it can be observed the detailed results regarding the scenarios compared in this section:

Time period or scenario	Price €/y	Annualised: cost €/year
00-07 h	0.25	23,333.33
07-13 h	0.31	28,933.33
13-18 h	0.28	26,133.33
18-24 h	0.35	32,666.67
Base scenario	0.06	5,600.00
0.1025 H2 kg/km	5.5	37,583.33
0.06 H2 kg/km	5.5	22,000.00
0.0354 H2 kg/km	5.5	12,980.00
0.1025 H2 kg/km	1.5	10,250.00

Table 38. Detailed results of the different scenarios analysed (Source: own elaboration).

Further studies on this matter would be needed. Approaches like Estrada, et al. (2022) with actualised data would help decision makers to optimise the charging strategies to adjust the purchasing cost and maximizing the batteries durability.

Assuming a battery pack of 198 kWh (Volvo, 2019) and same weight that (Nordelof, et al., 2019), it can be seen that if the charging strategy used is the opportunity charging, some of the environmental impacts are not reduced significantly. It is because these batteries require similar amount of materials. However, the purchasing cost of the new battery pack can be reduced because the batteries cost is related to the kWh of it, therefore if it reduced, the cost is as well reduced. The environmental impacts are only reduced a 4% on average. The biggest reduction is observed in the global warming potential, where the 330 kWh battery pack generated 3,1 kg CO_2 eq./ 100km against the 2,84 kg CO_2 eq./ 100km of the 198 kWh battery pack. This can be observed in the following figure:

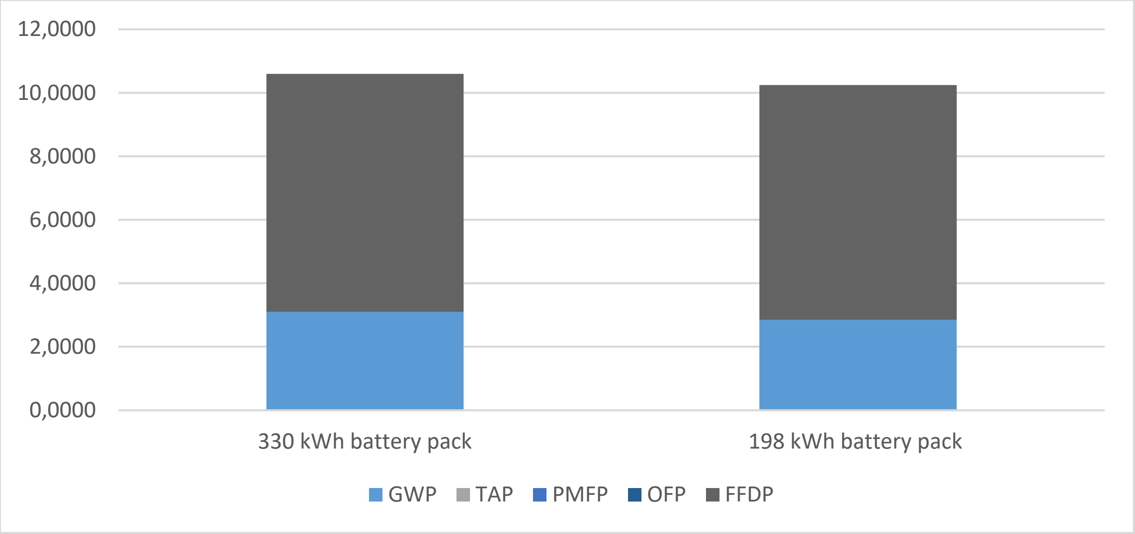


Figure 47. Aggregated potential environmental impacts of the battery pack compared (Source: own elaboration).

A detailed data of the results obtained by impact category can be seen in the following figure:

Kg x eq./100 km	GWP	TAP	PMFP	OFP	FFDP
330 kWh battery pack	3.0941	0.0026	0.0024	0.0047	7.4940
198 kWh battery pack	2.8401	0.0025	0.0024	0.0045	7.3920

Table 39. Detailed results obtained by different battery pack (Source: own elaboration).

The purchase price, assuming the same prices than other sections of this study (260 €/kWh (Estrada, et al., 2022)) is 51.480 € compared to the 85.800 € purchase cost of the 330 kWh battery pack. However, due to fast charging and variable conditions of this strategy of charging the lifespan of the battery can be reduced significantly (TMB, 2019). Therefore, the replacement cost is increased as well, and the competitiveness of the electric model would be reduced as well compared to the hydrogen model.

Consequently, the charging strategy play a significant role regarding the competitiveness of the model. As the prices of the electricity are increasing considerably, the strategies must be changed in order to adjust the purchase cost that would be higher of the hydrogen scenarios. At the same time, battery lifespan is other aspect to be considered, as higher rates of charging will decrease considerably the useful time. Turning into more replacement costs and more potential environmental impacts compared to the hydrogen bus.

8 Limitations

During the study, some limitation was founded related to the software used and the information available. Firstly, the study was based on LCA comparison of two different models. To do it, the life cycle phase of each vehicle were analysed and for the manufacture phase and maintenance phase, each of the component that forms the bus were modelled independently. Which means that all the materials and its weight were required to be listed. However, the information regarding these were not enough to make the model as detailed as possible and some assumptions were needed to proceed. For example, the information of the materials used to build the chassis and the vehicle body of the Caetano's model were not available. If LCA are keen to be more detailed and provide with more deep analyses, manufacturers should facilitate the materials used to build the components and the different process to do so. Besides, some misleading can be produced, as the results are absolute values and not specific impacts potentials, so further studies must be done to analyse these.

Following these, the data base of the Greet has some limitations regarding the materials and its pathways. Not all of the materials obtained during the desk research were modelled in the software used. Besides, datasets used would be more extensive and specific if the purchase cost was not that high. Specialised LCA datasets are extremely expensive (more than 3.000 € for an educational license) for projects such this; therefore, the achievable outcomes are limited. Therefore, some assumptions were required again, limiting in some grade the results obtained. In addition, the end-of-life phase was limited due to lack of a specific process. That is the reason of having the same impacts and emission for the different phases and models. There was no recycling process available, thus the decrease of that can be achieved with this phase was assumed the same as Davide, et al (2022) results.

In addition, other limitation observed was that Greet does not have outputs for the other pollutants and it was necessary to only compute the impact categories by using four pollutants. Which were NO_x, CO, CO_2, CH4 and the PM10 particles. Therefore, other relevant impact categories were no able to be proper determined. Such as Human

Toxicity, Water Eutrophication, Metal Depletion, Ozone depletion, Ionising radiation or Land-use (Goedkoop, et al., 2009).

9 Conclusions

Regarding the environmental impacts related to the results obtained by the LCA, it could be concluded that the electric Volvo 7900 Series meets better the sustainable objectives than the hydrogen CaetanoBus H2 City Gold model. Even though some phases during the life cycle of the vehicles are somehow similar. However, differences between the models can be observed in the manufacture phase, the well to pump phase and the maintenance stage.

In manufacture phase, the difference lays in the batteries and fuel cell system materials and manufacture. Therefore, as other components of the vehicle (i.e. chassis, vehicle body, electric motor, etc.) were supposed to be equal, the fuel cell manufacture is more harmful environmentally than the production of the batteries, also because it requires a pack of two lithium-ion battery. The on-board hydrogen tanks are also relevant components that contributes significantly to the emissions emitted during the manufacture phase. Materials such as carbon and glass fibbers, tetrafluoroethylene, platinum, graphite and plastic materials are the main contributors to the emissions compared to their percentage over the total mass of the vehicle. Nonetheless, batteries also contribute significantly to the emissions generated by both models. Materials like NMC 622, n-menthyk-2-pyrrolidone and Lipf6 are main contributors to the emissions generated compared to their percentage over the total mass of the vehicle.

Maintenance phase is also related to manufacture stage. This is because the maintenance stage considers only the replacements of batteries, fuel cell stacks, vehicle fluid and tires. The replacements take into account all the manufacture process as well, so the potential environmental impacts are per unit of component replaced, the same as the manufacture phase. However, in this stage, the regularity of the replacement is the key parameter. Therefore, in this stage the electric model generated more emissions than the fuel cell bus, as the batteries has less assumed lifespan than the fuel cell (respectively 220.000 and 240.000 km) and they have to be replaced three and two times respectively. The difference seems not to be relevant, however the total amount of the batteries required driving the electric bus is significant higher than the fuel cell stack and the two batteries required for the hydrogen bus that only requires two. However, it is observed a small difference in terms of GWP, as the hydrogen has 10,8 kg CO_2 eq./ 100km and the electric model 11,7 kg CO_2 eq./ 100km (8% of difference). However, the other impact categories possess a higher difference, between 39%and 60% less environmental impact of the hydrogen model against the electrical vehicle. Which is observed to be more harmful specially to human health (higher production of PM10 particles than hydrogen bus).

It is also important to comment that, the main differences observed regarding the life cycle emissions are related to Global Warming Potential and fossil fuel depletion potential. The other pollutant equivalent emission is similar between each other. The global warming potential is 121% higher in the case of hydrogen model against the electric bus. Respectively, the emissions are 134,1 kg CO_2 eq./ 100km and 60,7 kg CO_2 eq./ 100km. Regarding fossil fuel depletion, the difference is about 80% higher again in the case of the hydrogen model versus the electrical option. The FFDP of the hydrogen bus was equal to 120 kg oil eq. /100km and the electric vehicle has 66,9 kg oil eq. /100km.

The well to pump phase is considerably a milestone in the LCA of both model as is the phase with the biggest difference considering the emissions generated. Hydrogen production is by far, the most harmful production process. As the present study assumed that the base scenario is based on grey hydrogen, the difference versus the electricity production is significant high. The electricity mix has a relevant share of renewable energy and low CO_2 emission energies (i.e. nuclear energy), which permits to generate 37,6 kg CO_2 eq./ 100km. however, the hydrogen production is based on natural gas reforming, which means that is fully based on fossil fuels and its negative impacts on the environment. The emission generated due to this process are equal to 110,6 kg CO_2 eq./ 100km, which is 194% higher than the electricity production. Besides, the fossil fuel is more relevant on the hydrogen production, with a difference of 485% larger than the fossil depletion regarding electricity production. These impacts, on the other hand can be drastically reduced if green hydrogen is produced. As commented in the competitive analysis, grey hydrogen is a huge detriment in terms of environmental impacts (as well as the hydrogen produced by the Spain electricity mix electrolysis). However, green hydrogen states as a significant appropriate fuel option, having minimum harmful impacts. Green hydrogen means and average reduction of 93% in the impact categories compared to the grey hydrogen and decrease of 87% of the emissions generated by the electric production. For example, the GWP was equal to 4,99 kg CO_2 eq./ 100km (110,63 kg CO_2 eq./ 100km for grey production and 37,59 kg CO_2 eq./ 100km for electricity production).

The divergence in the fuel used plays a significant role in terms of environmental impacts, but also it affects the cost of ownership of each vehicle. As it has been commented, the hydrogen price is considerably higher than the electric price, independently of the type of hydrogen used. The price of grey hydrogen is 1,5 €/kg H2 and the green hydrogen price is 5,5 €/kg H2, which compared to the electric price are significant higher. The base scenarios cost of purchasing the fuel are equal to 10.250 €/year for the grey hydrogen, 37.583 €/year for the green hydrogen and 5.600 €/year for the electricity purchase. The differences are significant; however, some improvements of consumption rates of the hydrogen would be beneficious in terms of fuel purchasing cost. In that sense, consumption rate of 3,54 kg H2/100km by maintaining the same grey hydrogen price would boost the competitiveness of the hydrogen model, as the cost of fuel purchasing would be 37% cheaper than the electricity cost. Besides, if the prince of the green hydrogen can be reduced under the euro and the consumption rate is 10,25 kg H2/100km, the cost of hydrogen purchase would be the same as the electrical option (plus all the environmental benefits related). If the electrical price increase, as it were observed in the past years in Spain, the electrical and its benefits would be less relevant. The related costs can be increased until 32.667 €/year depending of the time period used to charge the electric vehicles (this scenario's time period is between 18h and 24h). If the electricity price is maintained higher than 0,35 €/kWh, the competitiveness is lost against the green hydrogen powered vehicles, which fuel purchasing cost would be similar but with a significant reduction of potential environmental impacts. Therefore, boosting the decarbonisation of the transit mobility. However, further studies in charging strategies that equilibrates the battery durability and limits the purchasing cost would help to mitigate the negative impacts of the new electricity prices regulation. The related cost of replacements and maintenance of the hydrogen bus are lower than the electrical bus. Which can allow compensating the higher cost of vehicle purchase. The cost of replacement of the electric vehicles are due to higher scheduled batteries replacements, which is equivalent to 21.430 €/year compared to 17.720 €/years of the hydrogen model.

However, the greater dissimilarities are related to infrastructure investment and maintenance cost. If this costs are neglected, the difference between the cost of ownership is only a 3%, 125,678 €/year for the hydrogen vehicle and 121.747 €/year. The higher investment costs of construction of new on-site production refuelling stations is a barrier to impediment hydrogen as an option for decarbonisation of mobility. Mainly because the facility is more complex than the installation of chargers (is required the construction of an electrolyser, a compression system, on-site storage tanks, refrigeration systems, dispensers and other complementary systems) and hence more costly to maintain. Therefore, programmes to invest in new on-site green hydrogen production refuelling stations must consider more than one operator or client to mitigate and dilute the investment cost in more than one user. For example, be able to refuel delivery vehicles and private vehicles.

Bearing in mind all the aspects, hydrogen mobility requires certain technological investments and improvements and to achieve economies of scale in order to be a serious option to ensure decarbonisation of mobility. Nonetheless, it is well known that the efforts have been focused on electro-mobility rather than hydrogen mobility. Therefore, the electric technology is more advanced than hydrogen and some economies of scale are being achieved as the cost of purchasing are decreasing compared to the first wave of electric vehicles. Consequently, the electric bus is more competitive than the hydrogen vehicle, which technology is starting its further development. While the former is being investigated and improved, the former will be also as well but it need to be more disruptive in order to achieve the same impacts and competitiveness. A key aspect is to put the hydrogen as the element to decrease the environmental impact of mobility. It does not have to be all the mobility. By avoiding car vehicles which is mostly focused on electro-mobility, high range services should put hydrogen as the alternative to be chosen. Hydrogen as fuel proved more range than the electric batteries, therefore transit systems, aviation and maritime sector could be benefit to embrace this technology. Consequently, investments are required to achieve better competitive and institutions like the Europe Commission could push forward the hydrogen technology.

Henceforward, green hydrogen is the best option to propel hydrogen models and more environmentally attractive than the electricity production and electric buses. However, in order to implement this type of hydrogen some elements must change to improve the competitiveness against electric model. Rate consumptions, vehicle purchase cost, infrastructure investment and most important, the cost of the hydrogen must decrease to become a real alternative. Hence, governments must improve hydrogen development investment to optimize and boost the implementation process. Nonetheless, electro-mobility is facing serious issued due to electricity prices, which are escalating considerably. This would lead to a loss of competitiveness against hydrogen options, as the charging prices would be enormous if the optimal charging strategies are not well design, planed and implemented. Finally, battery reliability is still an issue to overcome to ensure a widely and more rapid implementation, especially when considering super-charging strategies that tries to meet the time periods when the electricity prices are cheaper.

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