Water-tightness Airborne Detection Implementation

D7.1. LCA Report

Authors: CIRCE

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Technical references

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PP = Restricted to other programme participants (including the Commission Services)

RE = Restricted to a group specified by the consortium (including the Commission Services)

CO = Confidential, only for members of the consortium (including the Commission Services)

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Disclaimer

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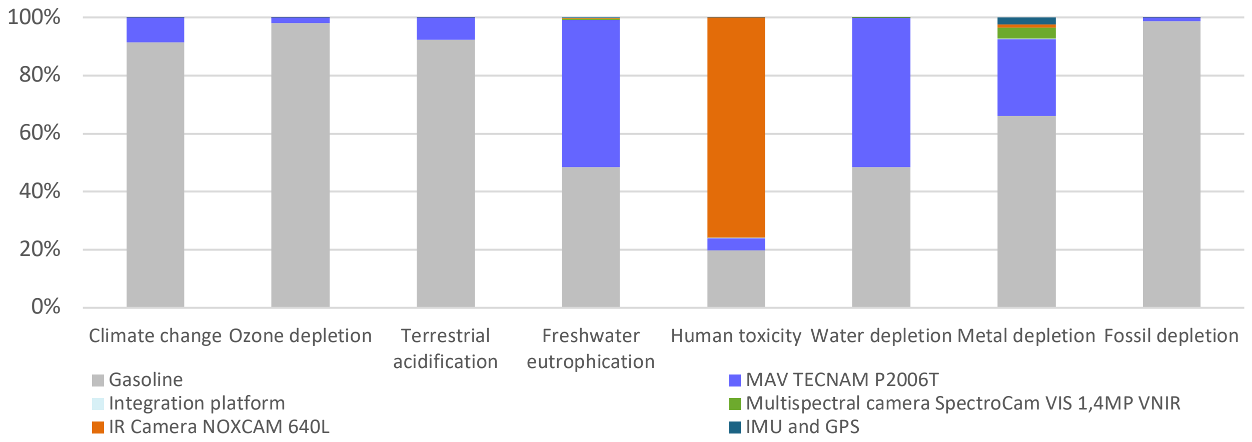
Executive Summary

This deliverable contains the results obtained from the Life Cycle Assessment (LCA) of the two WADI units developed in the project: MAV and UAV. To develop this analysis, it was applied the methodology described in ISO 14040:2006.

The main objectives of this deliverable can be summarized in the following points:

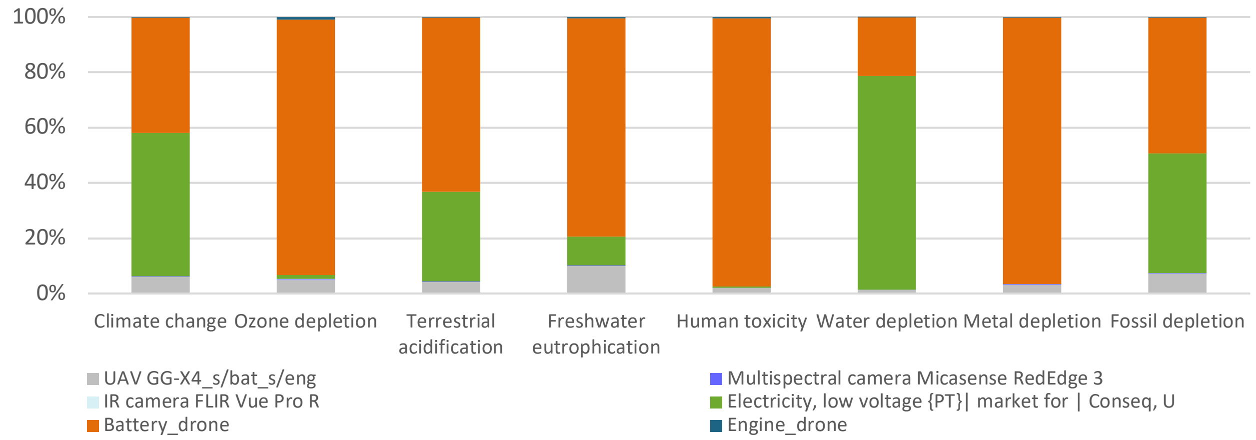
- Perform an inventory analysis by means of quantifying all the energy and material flows, as well as the incoming and outgoing materials (extracted or emitted into the environment) required during the manufacturing processes of the new WADI units and the useful lifetime of the demonstrators involved in the project.
- Calculation of the most relevant environmental impacts indicators associated with the WADI water leaks detection techniques in order to be compared with the potential environmental improvements that could be achieved thanks to the WADI project development.

As main conclusions obtained from this study, when the MAV unit is analysed, the results obtained are depicted in the figure below. The carbon footprint of this unit is about 270,000 kg CO_2eq and the water footprint is 158,000 m^3. The greatest contributor to most of the environmental categories is the impact associated with the fuel consumed during the aircraft flights. Besides, it is very relevant the contribution of the plane manufacturing over some indicators such as freshwater eutrophication and water depletion, and the contribution of the IR camera over the human toxicity indicator.



Relative environmental impact per indicator of the MAV WADI unit

Regarding the UAV unit, its carbon footprint is 545 kg CO_2eq and the water footprint is about 7,300 m^3. The relative environmental impact of the UAV components, as well as the impacts of the consumption involved during the use stage are depicted in the figure below. The drone batteries have the greatest contribution in many environmental categories such as ozone depletion, human toxicity or metal depletion. This fact is mainly caused by the periodicity with which the batteries must be replaced along the lifetime of the drone. On the other hand, the electricity consumption required to charge the batteries has the greatest impact in the climate change indicator and in the water and fossil fuel depletion indicators. In this case, it is very important to specify the electricity mix of which country is used because the results can significantly vary.



Relative environmental impact per indicator of the UAV WADI unit (Portuguese electricity mix)

Finally, if the results obtained from the LCA studies are compared with the potential impacts that could be achieved by the WADI technology through a successful business model, the environmental opportunities presented by the WADI water leaks detection techniques are huge and the burdens associate with the manufacturing and the using stages of both systems are small in comparison to the environmental benefits achieved.

In a final step, a comparison from LCA perspective of WADI techniques and acoustic methods (as the most usual method for leak detection, and the method used in WP5 and WP6 to check WADI reliability) has been done.

Table of Content

1 Introduction

The main objective of WADI project is to contribute to the reduction of water losses in water transmission systems and to decrease the related energy consumption required for the process.

Water is increasingly becoming more valuable due to scarcity in many regions. This is the reason why the status of the transmission and distribution systems is a key factor to assure enough quantity and quality of water in Europe.

WADI project aims to investigate a new water detection technique deployed on two platforms (manned & unmanned) in order to achieve a better analysis of European water network. This technique is based on innovative optical remote sensing integrated in aircrafts. It consists of **manned aircraft flights (MAV)** and, **unmanned flights (UAV)** using **drones** equipped also with **two different optical devices** (**multispectral** and **IR cameras**).

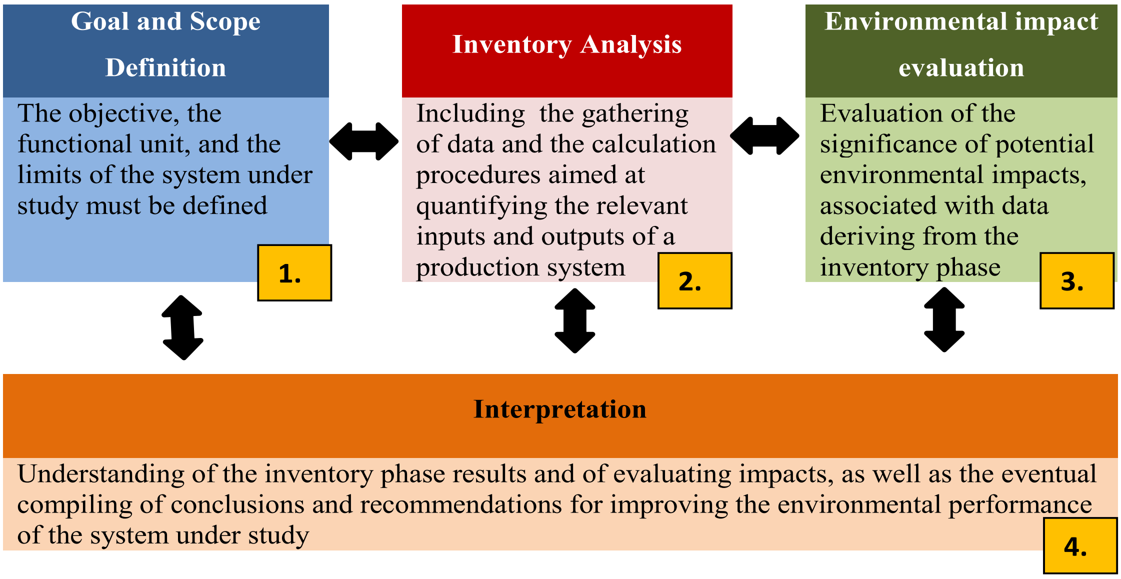
Water leaks detection using WADI technique is expected to increase water availability and thus, avoid resources depletion and environmental impacts related to the energy consumption of water networks. In this sense, performing an environmental evaluation of these detection methods is crucial to assess how the implementation of WADI technique affects different environmental categories such as climate change or water depletion.

2 LCA methodology

The **Life Cycle Analysis methodology (LCA) is useful for analysing the environmental impact** caused by any type of process and product [5]. The society of Environmental Toxicology and Chemistry (SETAC) defines LCA as “an objective process to evaluate the environmental burdens associated with a product, processor activity by identifying energy and materials used and wastes released to the environment, and to evaluate and implement opportunities to achieve environmental improvements”. In other words, LCA studies cover the environmental aspects and potential impacts throughout a product’s life (i.e. cradle-to-grave) from raw material acquisition, via production and use phases, to waste management.

Regulation of the development of good quality LCA studies is compiled in standard UNE-EN ISO 14040:2006 [1]. Here, it is specified that a LCA is usually performed following four main stages, see Figure 2-1:

1. Goal and scope definition
2. Inventory analysis
3. Environmental impacts evaluation
4. Interpretation



Goal and Scope Definition

The objective, the functional unit, and the limits of the system under study must be defined

1.

Inventory Analysis

Including the gathering of data and the calculation procedures aimed at quantifying the relevant inputs and outputs of a production system

2.

Environmental impact evaluation

Evaluation of the significance of potential environmental impacts, associated with data deriving from the inventory phase

3.

Interpretation

Understanding of the inventory phase results and of evaluating impacts, as well as the eventual compiling of conclusions and recommendations for improving the environmental performance of the system under study

4.

Figure 2-1: Main stages of a LCA study.

The **goal and scope definition** stage is the first step in a LCA study in which the product or process to be assessed is defined, and so is the context of the study. The importance of this stage lies in the crucial connection between the purpose of the study and the system boundaries definition.

In this stage, many parameters have to be identified: time and resources needed, purpose of the study, intended application, system boundaries, methodology and general assumptions and limitations [2]. The most important points to be analyzed and fixed in this stage are the **system boundaries** and the **functional unit** (a quantitative description of the service performance of the case study or a quantitative description of products).

After this stage, the **inventory analysis** (LCI) is performed by means of data collection in collaboration with all the partners involved in the project. This data collection is restricted to the system boundaries previously identified.

Finally, stages 3 and 4 consist on the **environmental assessment** by itself. The environmental impact is determined for a serial of selected indicators, which are related to the calculation method applied in the study. Results of this analysis have, in the last phase of the LCA, to be **interpreted** to firstly summarize LCI and LCA results and then, discussed and reviewed to obtain conclusions, recommendations, depending on the goal and scope definition.

3 Environmental analysis

3.1 Goal scope and functional unit definition

The objective of this task is to perform an environmental analysis of both leak detection technologies. For the manned aircraft, **raw materials** extraction and processing, aircraft **manufacturing**, **use** phase and **end-of-life** strategies were included in the analysis. These phases were selected as the most *"impacting"* ones according to literature [4].

As an example of LCA studies applied to aircrafts,**Errore. L'origine riferimento non è stata trovata.** Figure 3-1 shows the flow diagram of an aircraft life cycle [3]. Different phases are identified in the diagram, as well as the different resources that are consumed in each stage.

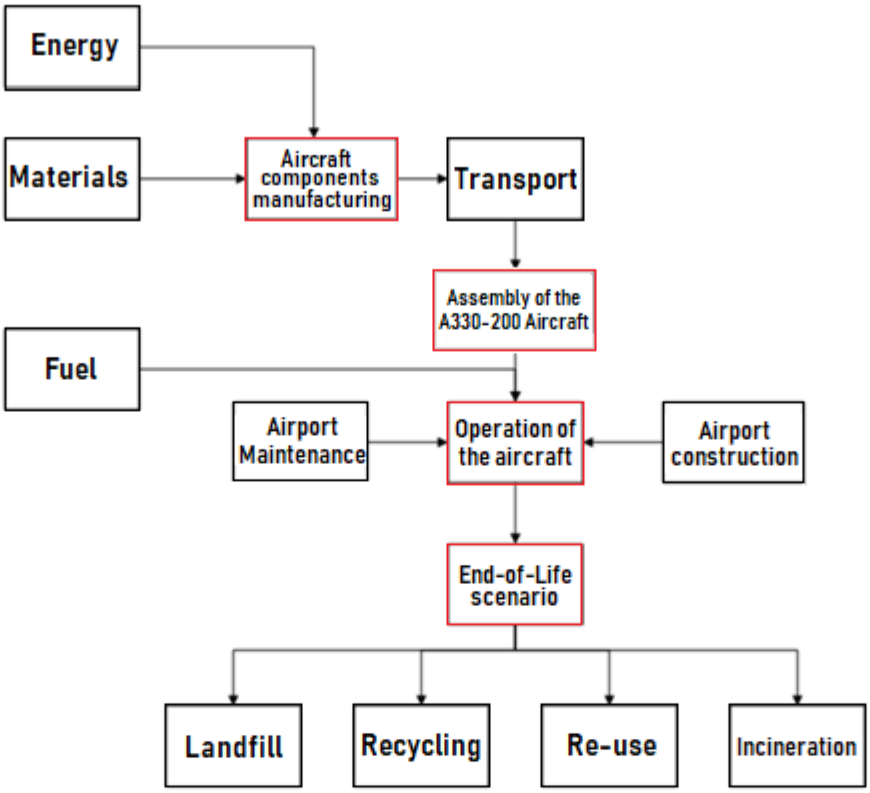


Figure 3-1: Flow diagram of the A33-200 life cycle [3]

Finally, regarding the **functional unit**, Table 3-1 includes those selected for the analysed technologies within the framework of WADI project.

Detection technique	Functional unit
Manned aircraft	1 aircraft WADI unit (TECNAM P2006T+platform+cameras)
Drone	1 drone WADI unit (Model GG-X4+cameras)

Table 3-1: Functional unit considered for each WADI detection system

3.2 System boundaries

The system boundaries of the analyses performed in WP7 were set considering both the information available and the characteristics of the leak detection task itself. As foreground process, this is, those processes from which data can be directly measured and collected from the responsible companies, the analysis considered the manufacturing and use stages. On the other hand, the background processes, or what is the same, the processes defined by means of generic data taken from life cycle inventory databases, e.g. from commercial databases, were the raw material extraction and transformation, and the end-of-life strategies. Figure 3-2 depicts a scheme for an aircraft life cycle, taking into account from the materials extraction to the end-of-life of the aircraft.

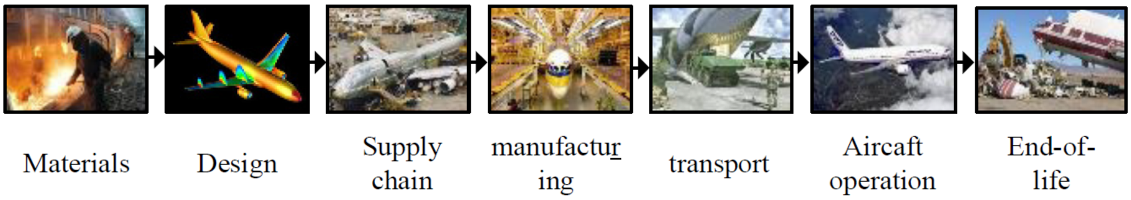


Figure 3-2: Aircraft life cycle [6]

As mentioned above, a cradle-to-grave analysis was performed to both leak detection techniques. On the one hand, and in order to better identify the contribution of each component to the total environmental burden of the WADI solutions, a more detailed evaluation of the manufacturing stage was carried out. On the other hand, the most common end-of-life strategies have been identified and described in the last part of this deliverable, but the impact associated with them has not been quantitatively calculated. In this light, the current deliverable includes a cradle to gate evaluation of both the MAV and UAV units.

Regarding LCA impacts calculation, the study was performed according to ReCiPe Midpoint (H) V1.08 / Europe Recipe H method, excluding infrastructures. Nevertheless, infrastructures had to be considered in the UAV electric motor impacts analysis because this component is classified as infrastructure by Ecoinvent. The electric motor of the drone was the only one analysed including infrastructures because the impacts analysis without infrastructures was more representative.

Finally, since the direct electricity consumption is a critical LCI parameter that can significantly influence the environmental burden of the drone use stage, this study has considered the electric mix in the country where the flights take place. In consequence, the French and Portuguese mix of electricity have been taken into account.

3.3 Environmental impact indicators

The environmental analysis was performed by using midpoint approach impact category indicators. The different impact categories of the ReCiPe method and the measurement units that can be calculated are shown in Table 3-2.

Table 3-2: *Impact categories included within the ReCiPe method and their units*

Environmental impact category	Units
Climate change	**kg CO_2 eq**
Ozone depletion potential	**kg CFC-11 eq**
Terrestrial acidification	**kg SO_2 eq**
Freshwater eutrophication	**kg P eq**
Marine eutrophication	kg N eq
Human toxicity	**kg 1,4-DB eq**
Photochemical oxidant formation	kg NMVOC
Particulate matter formation	kg PM10 eq
Terrestrial ecotoxicity	kg 1,4-DB eq
Freshwater ecotoxicity	kg 1,4-DB eq
Marine ecotoxicity	kg 1,4-DB eq
Ionising radiation	kBq U_{235} eq
Agricultural land occupation	m^2a
Urban land occupation	m^2a
Natural land transformation	m^2
Water depletion	**m^3**
Metal depletion	**kg Fe eq**
Fossil depletion	**kg oil eq**

Eight of these indicators are marked in bold because they are considered as the most relevant indicators for this project [8] and they will be analysed with more detail along this deliverable. These indicators are:

- **Climate Change**: It is a major global problem nowadays, and reducing this impact is one of the main achievements that are expected out of this project. It is measured in kg of CO_2 equivalent referred to the functional unit of this analysis.
- **Ozone Depletion Potential** accounts for the destruction of the stratospheric ozone layer by anthropogenic emissions of ozone depleting substances and uses CFC-11 (trichlorofluoromethane) as a reference compound.
- **Terrestrial Acidification** is a measure of emissions that cause acidifying effects to the environment. It is expressed as kg SO_2 equivalent that provides an equivalent estimate of air pollutants emission. The major acidifying emissions are nitrogen oxides (NO_x) and sulphur dioxide (SO_2).
- **Eutrophication of Fresh Water** can be defined as the over-enrichment of watercourses with ammonia, nitrates, nitrogen oxides and phosphorous. Its occurrence can lead to damage of ecosystems, increasing mortality of aquatic fauna and flora and to loss of species dependent on low-nutrient environments. Eutrophication potential is expressed using the reference compound in kg PO_4 equivalents.
- **Human Toxicity:** This indicator assesses the effect of a chemical in function of the environmental persistence (fate), the accumulation in the human food chain

(exposure) and toxicity (effect) of the chemical. It is measured in kg 1,4 dichlorobenzene (1,4-DB eq.).

- **Water depletion:** Water consumption is the use of water in such a way that water is evaporated, incorporated into products, transferred to other watersheds, or disposed into the sea. Water that has been consumed is, thus, not available anymore in the watershed of origin for humans nor for ecosystems.
- **Metal depletion:** This indicator is related with mineral resource scarcity. It represents is the surplus ore potential.
- **Fossil depletion:** The characterization factor of fossil resource scarcity is the fossil fuel potential, based on the higher heating value. The unit is kg oil equivalents.

All the previous indicators can be included into the category of midpoint indicators. Midpoints can be defined as links in the cause-effect chains of an impact category. On the other hand, endpoints are related with the relative importance of emissions or extractions [7]. Figure 3-3 depicts the relationships between all the midpoint impact categories and the endpoint categories: damage to human health, damage to ecosystems and damage to resource availability. In this study, midpoints were selected to be calculated since they are more representative of the environmental mechanisms.

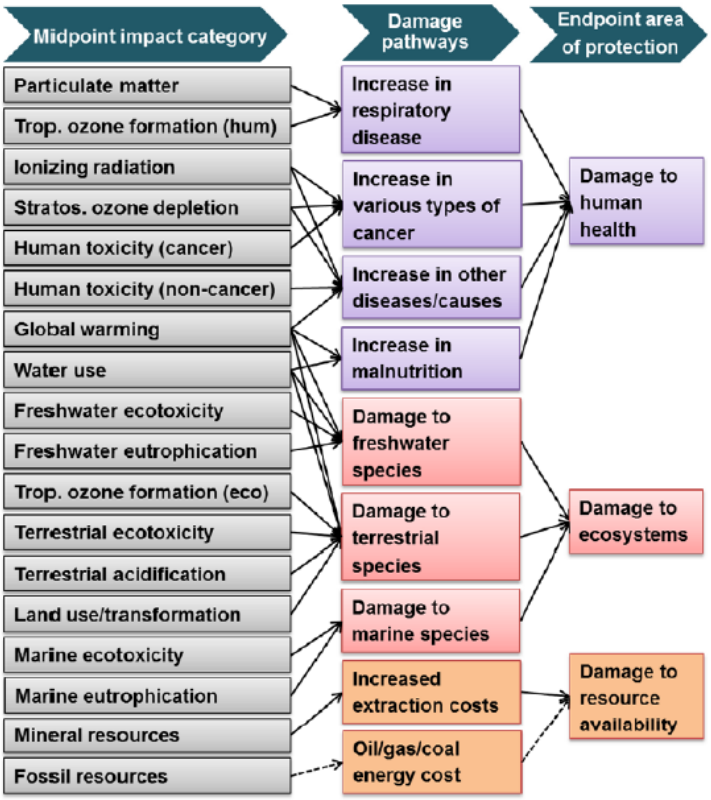


Figure 3-3: Representation of the relations between the impact categories midpoint and the areas of protection (endpoint) [8]

3.4 Software and databases

The environmental analysis was performed using a software and some databases included in the former. Besides the database developed in the framework of WADI project, which compiles the information provided by partners, some extra literature data were also used.

SIMAPRO 8.5 was the software chosen to develop the LCA study. It is a flexible and well-designed tool for these analyses, based on ISO 14040. This software can simulate complex parametric models in different scenarios and calculate sensitivity analysis and statistical analysis.

On the other hand, the databases chosen for this work were:

- **ECOINVENT database**: developed by ETH (Swiss Research Institute). It deals with energy generation, mineral resource extraction and basic industrial processes, waste treatment and transport [9].
- The **European reference Life Cycle Database** (ELCD) is a database established by the European Commission's Joint Research Centre (JRC) and integrated in the SimaPro LCA Software [10]. The ELCD database contains data from industries such as the chemical and metal industry. It also includes data on energy production, transport and end-of-life processes. The datasets are provided and approved by their respective industry associations.

4 Aircrafts LCI

Once the scope and system boundaries are defined, the next step to perform a Life Cycle Assessment analysis is to elaborate an inventory (LCI) of the different components and materials included in each stage. For this purpose, the LCI has been divided into two sections: the first one considers all the components and consumptions required to manufacture on unit of MAV or UAV; this analysis is called as cradle to gate study. On the other hand, the second section considers all the consumptions incurred during the use stage of each WADI unit, as well as the lifetime of each component and its replacement period.

4.1 Manned Aircraft Vehicle (MAV) LCI

4.1.1 MAV manufacturing LCI

As it was previously defined, the first leak detection technique consists of manned aircraft flights to monitor large areas by long-distance flights and important infrastructure. LCI of the MAV manufacturing was performed considering as **functional unit one unit of aircraft** with all the **cameras and instrumentation** required for the water leaks detection.

In order to illustrate the materials that are included in the Life Cycle Inventory, Figure 4-1 shows a picture of the aircraft selected for the WADI project; Figure 4-2 presents an scheme of the camera integration platform for the MAV and Figure 4-3 depicts two pictures of both selected cameras: multispectral and infra-red.

Figure 4-1: Aircraft TECNAM 2006T. Source: [11]

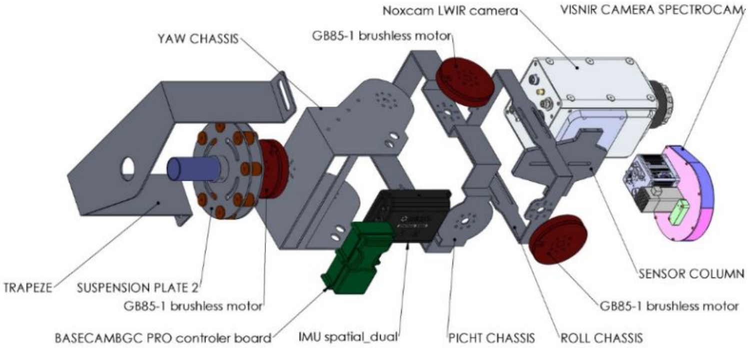


Figure 4-2: Camera integration platform

Figure 4-3: Left: Multispectral Camera SpectroCam [12]. Right: IR Camera NoxCam 640L [13]

The gathered information for the Manned Aircraft (MAV) is included from Table 4-1 to

Table 4-5. The first of them (Table 4-1) is referred to technical specifications of the manned aircraft itself, Table 4-2 includes the inertial measurement unit information,

Table 4-3 and

Table 4-4 depict the components and materials of the multispectral and IR cameras respectively and

Table 4-5 shows the information regarding the integration platform.

Table 4-1: Technical characteristics and components of the Manned Aircraft

	TECNAM P2006T	Value	Unit
General information	Empty Weight [1]	800	kg
	Maximum Weight	1230	kg
	Expected lifetime (from now)	22	years
Materials of construction	Aluminium alloy (main material)	718	kg
	Glass	2	kg
	Fuselage	N/A	kg
	Electronics and computer	30	kg
	Landing gear	50	kg
Engines (75 kW)	Engines	2	units
	Power of engines	75	kW
	Type of fuel	Avgas100ll or EN228 premium	
	Consumption during flight	38	l/h

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[1] The value of empty weight is referred to the aircraft without cameras, fuel, passengers or any other load and the maximum weight is related to the load it can support.

Table 4-2: Technical characteristics and components of the Inertial Measurement Unit MAV

Name		Value	Unit
Inertial Measurement Unit (IMU) and GPS Spatial dual EK – Advanced Navigation	Size	90*127*31	mm*mm*mm
	Power consumption	2.64	W
	Total weight	0.285	kg
	Expected lifetime (max uses)	10	years
Materials	Case (plastic)	0.057	kg
	Electronics and cable	0.228	kg

Table 4-3: Technical characteristics and components of the Multispectral Camera MAV

Name		Value	Unit
Multispectral camera SpectroCam VIS 1,4MP VNIR	Power consumption	10	W
	Size	138*124*98	mm*mm*mm
	Total weight	0.8	kg
	Present lifetime	6	years
	Expected lifetime (maximum uses)	N/A	years
Materials	Lenses	0.4	kg
	Lenses protector (plastic)	0.05	kg

Table 4-4: Technical characteristics and components of the IR Camera MAV

Name		Value	Unit
IR Camera NOXCAM 640L	Type	Cooled LWIR	
	Size	360*120*113	mm*mm*mm
	Power consumption	25-40	W
	Total weight	3,3	kg
	Expected lifetime (max uses)	8500	hours
Materials	Lenses	0.3	kg
	Infrared	0.57	kg
	Electronics and cable	0.33	kg

Table 4-5: Technical characteristics and components of the Integration Platform MAV

Name		Value	Unit
Integration platform	Weight total	11.12	kg
	Size	340X275X360	m*m*m
	Power consumption	NA	W
	Expected lifetime	>10<20	years

	Electricity for construction	1.1	kWh
Materials	GB-85 motor	0.72	kg
	BaseCamBGC Pro	0.93	kg
	Nuvo-5000E/P	4.4	kg
	Spatial Dual	0.28	kg
	Trapeze	0.6	kg
	Suspension Plate	0.14	kg
	Yaw Chassis	0.5	kg
	Roll chassis	0.4	kg
	Sensor column	0.2	kg
	Pitch chassis	0.4	kg
	Bolts	2.5	kg
	Cable	0.05	kg

Finally, Table 4-6 contains a summary of the amount of each material considered for the manufacturing of the different MAV components in terms of the functional unit previously defined. Several assumptions have been performed to complete this table:

- In the Inertial Measurement Unit [14], 20 % of the total weight was considered to be the plastic case and the rest was assumed to be electronic components. See an example of an Advanced Navigation system in Figure 4-4.

Figure 4-4: Advanced navigation system image

- In the IR Camera, it was assumed 70 % of aluminium and 30 % of germanium for the lenses and 25 % of the total weight for the frame. Regarding the IR element, it is composed of mercury, cadmium and tellurium, according to the information provided by the partners. In order to determine the proportion of each element, some bibliography was checked [15], [16] and weight fractions were calculated taking into account that detection in the MWIR and LWIR windows is obtained using 30 % $[(Hg_{0.7}Cd_{0.3})Te]$ and 20 % $[(Hg_{0.8}Cd_{0.2})Te]$ respectively [16]. Finally, the rest of the total weight, deducting the known components weight, was considered to be plastic.
- Regarding the manned aircraft, TECNAM P2006T, the engines model is Rotax 912, which corresponds to a four-cylinder four-stroke engine. As no aircraft engine with these characteristics was found in SimaPro, it was selected an internal combustion engine of a car but considering the weight of the aircraft engine.

Regarding the databases utilised to perform the inventory, most of the elements were selected from Ecoinvent 3 database and some others from the European Life Cycle Database (ELCD).

Table 4-6: MAV Life Cycle Inventory

Component	Material	unit/ component	Unit /WADI unit	Unit
Aircraft	Aluminium	718	718	kg
	Plexiglass	2		kg
	Electronics	30		kg
	Steel	50		kg
	Engines	75	150	kW
Inertial Measurement Unit (IMU) and GPS Spatial dual EK – Advanced Navigation	Plastic	0.06	0.06	kg
	Electronics	0.23	0.23	kg
Multispectral camera SpectroCam VIS 1,4MP VNIR	Lenses (glass)	0.4	0.4	kg
	Plastic	0.05	0.05	kg
	Electronics	0.35	0.35	kg
IR Camera NOXCAM 640L	Aluminium	1.03	1.03	kg
	Germanium	0.09	0.09	kg
	Mercury	0.28	0.28	kg
	Cadmium	0.05	0.05	kg
	Tellure	0.24	0.24	kg
	Electronics	0.33	0.33	kg
	Plastic	1.27	1.27	kg
Integration platform	Aluminium	7.64	7.64	kg
	Plastic	0.93	0.93	kg
	Stainless Steel	2.50	2.50	kg
	Cable	0.05	0.05	kg

4.1.2 MAV operation LCI

In the LCI study of the MAV manufacturing stage, all the components of the WADI unit have been identified. However, it was considering the impact of manufacturing one unit of MAV without taken into account the lifetime of each component and the amount of times that they must be replaced along the use stage. For this reason, this section provides a wider perspective of the LCA, including not only the replacement rate of each component but also all the consumptions incurred when the MAV is being used until the end of its useful lifetime.

The most important consumption of the MAV during the use stage is the fuel for the aircraft. In order to determine its consumption, it was agreed by Air Marine that a realistic average consumption could be 40 l/h. The effective use of the plane in a year was considered 400 h/year, what means that 16,000 l of fuel are consumed each year by a MAV. The kind of fuel consumed is AVGAS100LL. Avgas is part of the gasoline family and is designed for use in spark ignition engines. The octane grade of the used gasoline is 100/130. However, since it was not possible to find the environmental characterization of that fuel in the available environmental databases, a review was performed to find the most similar available alternative. Finally, even though the octane rating is lower, automotive gasoline was considered for the current study.

On the other hand, the lifetime of each MAV component has been estimated, as well as its annual effective use (Table 4-7). All that information was provided and validated by Air Marine. Depending on the service demand, the annual flight hours could significantly vary and therefore, the environmental impact allocated to the WADI service too. In this sense, the current study should be revised if substantial differences are detected when the WADI service is marketed.

Table 4-7. Lifetime of the most relevant components of the MAV

Component	Lifetime [years]	
Plane	30	400 h/year
Integration platform	20	1325 h/year
IR camera	6	8500 h/lifetime
Multispectral camera	6	400 h/year
IMU – GPS unit	20	400 h/year
Console	15	400 h/year

4.2 Unmanned Aircraft Vehicle (UAV) LCI

The second technology selected in the WADI project is the unmanned aircraft, which is a drone equipped with multispectral and infra-red cameras for surveying water networks with short conduits and areas with difficult access or requiring infrastructure or area scans. The following sections contains the LCI of the manufacturing and operation stages.

4.2.1 UAV manufacturing LCI

The functional unit used in the elaboration of the manufacturing LCI of the UAV is one unit on drone with all the cameras and devices required to detect water leaks.

The drone selected for WADI project is shown in Figure 4-5 and Figure 4-6 depicts a picture of both Multispectral and Infra-red cameras installed in the UAV.

Figure 4-5: Unmanned aircraft model GG-X4

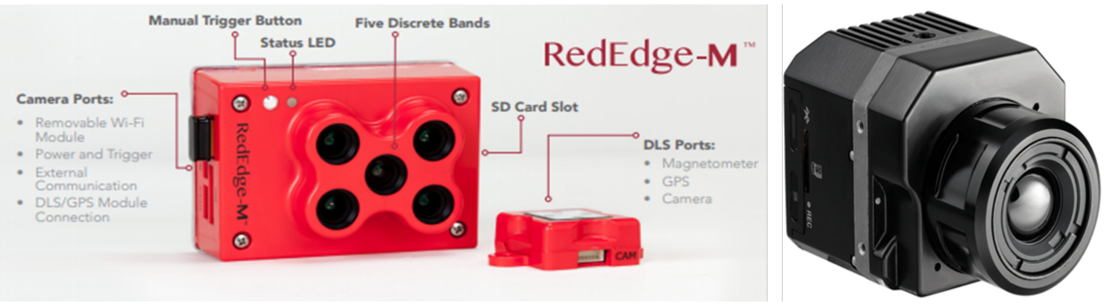


Figure 4-6: UAV cameras. Left: Multispectral RedEdge 3 Right: IR FLIR Vue Pro R

The procedure was performed by following the same methodology as in the manned aircraft data gathering. All the collected information is showed in Table 4-8 to

Table 4-10.

Table 4-8: Technical characteristics and components of the unmanned aircraft

Name	GG-X4	Value	Unit
General information	Size (length)	620x620x360	mm
	Wingspan	NA	m
	Type of drone	X4	
	Number of rotors	4	
	Type of GPS module	No RTK with magnetometer	
	Weight	3.5	kg
	Payload	5.5	kg
	Type of accelerometer	3 axes	
	Type of gyroscope	3 axes	
	Autonomy	12/18 + 2 (safety margin)	min
	Charging time	< 2	hours
	Range	7.5	km
	Current age	1	years
	Expected lifetime	10	years
Materials of construction	Main material	Carbon Fibre	
	Frame	Carbon fibre	
	Propellers, helix	Carbon fibre	
	Electronics, controller	Pixhawk	
	Batteries	1,6	units or kg

	Cables	4,5	m
	Engines	4	Units
	Power of engines	330	W
	Type of fuel	Electricity	
	Consumption during flight	22 – 31	A

Table 4-9: Technical characteristics and components of the Multispectral camera UAV

Name		Value	Unit
Multispectral camera Micasense RedEdge 3	Country of application	Both	---
	Total area of application	TBD	ha
	Area covered per flight	16-19	ha
	Power consumption	<2	W
	Size	121 x 66 x 46	mm*mm*mm
	Weight total	150	G
	Present lifetime	2	years
	Expected lifetime (maximum uses)	>10	years
Materials	Lenses	NA	kg
	Lenses protector (plastic)	NA	kg
	Frame	NA	kg
	Glass	NA	kg
	Electronics and cable	NA	kg
	Batteries	NA	units or kg
	Other parts/materials	NA	kg

Table 4-10: Technical characteristics and components of the IR Camera UAV

Name		Value	Unit
IR Camera FLIR Vue Pro R	Country of application	Both	---
	Total area of application	TBD	ha
	Area covered per flight	TBD	ha
	Type	LWIR	
	Size	63 x 44.5 x 44.5	mm*mm*mm
	Power consumption	2.1 (3.9)	W
	Weight total	95	g
	Present lifetime	1	years
	Expected lifetime (max uses)	>10	years
Materials	Lenses	NA	kg
	Lenses protector (plastic)	NA	kg
	Frame	NA	kg
	Infrared	NA	kg
	Batteries	NA	units or kg
	Electronics and cable	NA	kg
	Other parts/materials	NA	kg

From the previous tables, the following considerations must be considered:

- Carbon fibre is, as can be observed in Table 4-11, the main construction material of the UAV. Most of carbon fibre is made of polyacrylonitrile (PAN) [17], and this is the raw material considered for the drone carbon fibre.
- On the other hand, regarding cable, it was considered a 2.5 mm diameter copper wire. From this datum, weight was calculated to be introduced in SimaPro.
- The engine was considered to be similar to those used in electric scooters in regard to size, power, and model [18]. This is the reason why the input in SimaPro was considered: Electric motor, for electric scooter {GLO}| market for | Alloc Def, U. Moreover, the weight of the drone engine was assumed to be like the one published by Neuberger [18] (see LCI section).
- The information about materials included in the IR camera of the UAV was taken from the product datasheet [19], which revealed that the detector was an Uncooled VOx Microbolometer. According to a FLIR technical note [20], these detectors are made of vanadium oxide. As vanadium was not found in Simapro databases, the element with the most similar extraction process and environmental burdens was searched in the available databases. Finally, cobalt was selected for the IR detector in the UAV IR camera.

In order to perform the Life Cycle Assessment, all the components and materials of UAV are summarized in Table 4-11 and

Table 4-12. They are referred to the functional unit used for the LCA, which is one unit of UAV.

Table 4-11: total UAV Life Cycle Inventory

Component	Material	unit/ component	Unit / WADI unit	Unit
Drone	Carbon fibre	1.86	1.86	kg
Electronics	Pixhawk (electronics)	0,03	0.04	kg
Battery	Battery LiPo 6S/10 AH	1.6	1.6	kg
Cable	Cable	4.5		m
Engine		26.5	106	g
Multispectral camera	Micasense RedEdge 3	150	150	g
IR Camera	FLIR Vue Pro R	95	95	g

Table 4-12: Total UAV Life Cycle Inventory (per component)

Component	Material	unit/ component	Unit / WADI unit	Unit
Drone	Carbon fiber	1.56	1.56	kg
	Pixhawk (electronics)	0.04	0.04	kg
	Battery LiPo 6S/10 AH	1.6	1.6	kg
	Cable	4.5	4.5	m
	Engine	330	1320	W
Multispectral camera Micasense RedEdge 3	Lenses	75	75	g
	Case	9	9	
	Cable	1.5	1.5	
	CCD	64.5	64.5	

FLIR Vue Pro R	Lens	32.39	32.39	g
	Lens protector (plastic)	36.70	36.70	
	Infrared (Vox)	16.41	16.41	
	Electronics	7.60	7.60	
	Cable	1.90	1.90	

4.2.2 UAV operation LCI

Once analysed all the components and consumption involved in the manufacturing of one unit of UAV, the next step consists of preparing the LCI considering also its operation stage. For this study, it must be taken into account that not all the components of the UAV have the same lifetime. Some of them needs to be replaced several times during the lifetime of the drone. For this reason, it was essential for this study a close collaboration with Galileo Geosystems in order to proper estimate the durability of each component.

The durability of each component can vary depending on its effective use and the way it is used. For this reason, it was agreed by CIRCE and GG to define a life cycle scenario considering the average lifetime of each component under the following work routine:

- Every day, the effective flight time with the drone is 2.5 hours. This value was estimated considering that, in a workday, the person driving the drone needs to go to the area with potential water leaks and change several times its position in order to explore a wide section of pipelines.
- The flights can be done 20 days/month and 12 months/year (600 h/year). This scenario is quite optimistic because it considers that the innovative technology would have enough demand to operate during the whole year at full capacity.
- Every flight has a duration of 16 minutes (this is the duration of a battery). If the drone flights 2.5 hours every day, between 9 and 10 batteries must be consumed (and recharged) per working day.
- For this study, the lifetime of a drone was considered 5 years. The lifetime of a battery is about 2 years and then, it must be replaced. In 5 years, batteries must be replaced 2.5 times (total equivalent batteries required in 5 years is about 23 batteries).
- During the lifetime of the drone (5 years), the engine and the propellers must be replaced at least one time. For this reason, it was considered that the lifetime of these components is 2.5 years.

Considering the assumptions mentioned in the previous list, the lifetime considered for each component of the UAV system can be found in Table 4-13. The lifetime of the general structure of the drone was considered as reference unit; this is, 5 years. The table below contains the equivalent units of each component that are consumed in 5 years.

Table 4-13. Lifetime of the most relevant components of the UAV

Component	Lifetime [years]	Equivalent units in 5 years
Drone (general structure)	**5**	**Reference unit**
Multispectral camera	10	0.5
IR camera	10	0.5
Propeller	2.5	2
Engine	2.5	2

Batteries	2	23

Besides the replacement period of each component, the electric consumption of recharging the batteries must be included in the LCA of the UAV operation stage. To quantify this consumption, it was considered the following working methodology of GG:

- Each battery is composed by six elements. When the battery is full, the charge of each element is 4.12 volts (total: 24.72 v/battery).
- When the battery charge is about 20 volts, GG stops using that battery because of security reasons. Thus, the real volts consumed in each flight are 4.72 volts/battery.
- The batteries capacity is 10 amp-hour. Consequently, the electric consumption of each battery is 0.0472 kWh, or 0.4425 kWh/day considering that 9.375 eq-batteries are used each day.

Considering all the above, the electricity consumption of the drone batteries in 5 years can be found in Table 4-14.

Table 4-14. Total electricity consumption of the UAV during its lifetime

	Daily consumption	Total consumption (5 years)
Electricity consumption	**0.44 kWh**	**531 kWh**

5 Aircrafts LCA

5.1 Manned aircraft manufacturing (MAV) LCA

5.1.1 MAV manufacturing LCA

The first of the studies performed in this section corresponds to the manufacturing stage of the MAV unit. To this end, the LCI information presented in section **Errore. L'origine riferimento non è stata trovata.** allowed performing the environmental models and the subsequent analysis. The selected method to develop the LCA was ReCiPe Midpoint (H) method v 1.08, as explained above. For this analysis, materials inputs were selected from EcoInvent and ELCD databases.

Table 5-1 shows the environmental impacts for the different categories in absolute values. These impacts were evaluated for each component of the MAV WADI unit: aircraft, multispectral camera, IR camera and IMU-GPS system. The eighteen impact categories included in the selected method are collected in that table. Those selected as the most relevant indicators are marked in bold.

As an example, the carbon footprint per MAV WADI unit is 23100 kg CO$_2$-eq. and the water footprint is 157717 m^3/WADI unit. The manufacture of this unit also has an important impact on human toxicity indicator (25000 kg 1,4-DB), mainly due to the IR camera contribution.

Table 5-1: Environmental impact of one unit MAV manufacture

	Unit	Total	MAV TECNAM P2006T	Multispectral camera SpectroCam VIS 1,4MP VNIR	IR Camera NOXCAM 640L	IMU and GPS Spatial dual EK – Advanced Navigation	Integration platform
Climate change	**kg CO$_2$ eq**	**2.31E+04**	**2.30E+04**	**9.15**	**27.89**	**5.84**	**32.88**
Ozone depletion	**kg CFC-11 eq**	**1.79E-03**	**1.78E-03**	**7.18E-07**	**4.37E-06**	**5.18E-07**	**4.94E-06**
Terrestrial acidification	**kg SO$_2$ eq**	**109.84**	**109.57**	**7.29E-02**	**0.15**	**4.54E-02**	**0.13**
Freshwater eutrophication	**kg P eq**	**14.37**	**14.30**	**2.54E-02**	**2.68E-02**	**1.65E-02**	**6.43E-03**
Marine eutrophication	kg N eq	4.90	4.89	4.37E-03	6.18E-03	2.78E-03	3.67 E-03
Human toxicity	**kg 1,4-DB eq**	**2.50E+04**	**1,891.84**	**3.29**	**2.31E+04**	**2.15**	**4.56**
Photochemical oxidant formation	kg NMVOC	139.26	139.09	0.05	9.43E-02	0.03	0.09
Particulate matter formation	kg PM10 eq	43.10	42.99	0.03	5.93E-02	0.02	0.06
Terrestrial ecotoxicity	kg 1,4-DB eq	6.63	2.07	2.35E-03	4.56	1.52E-03	1.22E-03
Freshwater ecotoxicity	kg 1,4-DB eq	3.00	2.65	0.08	0.22	0.05	2.43E-03
Marine ecotoxicity	kg 1,4-DB eq	36.51	9.67	0.14	26.61	0.09	0.03
Ionising radiation	kBq U235 eq	6,581.28	6,576.48	1.47	2.40	0.94	3.24
Agricultural land occupation	m^{2}a	271.22	270.35	0.17	0.61	0.10	0.05
Urban land occupation	m^{2}a	81.61	81.31	0.10	0.13	6.54E-02	0.04

Natural land transformation	m^2	0.34	0.34	5.85E-04	7.25E-04	3.77E-04	2.35E-04
Water depletion	**m^3**	**157,717.14**	**157,614.87**	**34.28**	**46.02**	**21.96**	**24.48**
Metal depletion	**kg Fe eq**	**386.77**	**360.22**	**10.11**	**9.87**	**6.58**	**6.63**
Fossil depletion	**kg oil eq**	**6115.81**	**6.10E+03**	**2.51**	**7.26**	**1.61**	**8.00**

The highlighted impact categories were recalculated to obtain relative percentages and these relative weights are represented in Figure 5-1. In this graph, the importance of each component of the MAV-WADI unit can be analysed. The greatest contributor of almost all the impact categories is the aircraft itself (TECNAM P2006T), as expected. Nevertheless, it is important to emphasize the impact on human toxicity of the IR camera due to the composition of the IR detector. Next subsections will show with more detail the impacts of each component separately.

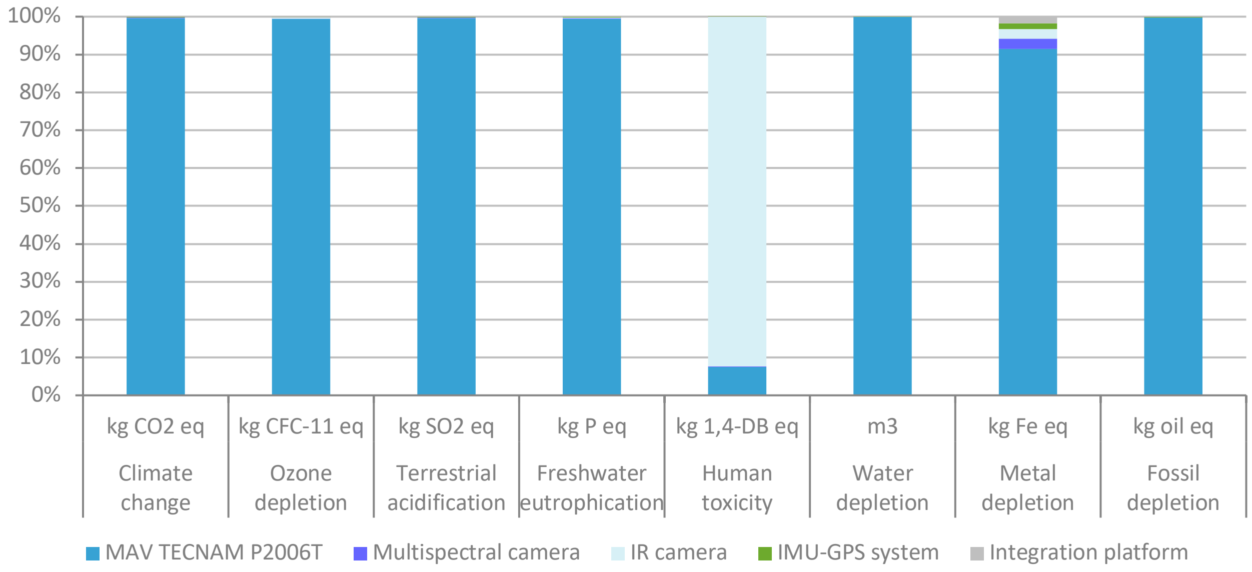


Figure 5-1: Relative environmental impact per indicator of a MAV unit

5.1.1.1 TECNAM P2006T aircraft

The aircraft selected for the MAV WADI unit was already described in section **Errore. L'origine riferimento non è stata trovata.**. In the material selection of SimaPro, a medium haul aircraft was selected from Ecoinvent database. This datasheet was modified taking into account the information supplied by partners and included in the LCI.

Figure 5-2 depicts the relative contribution of each component in the TECNAM 2006T aircraft. Aluminium from fuselage and electricity used in the manufacturing process are the main contributors to most of the impact categories, specially, to human toxicity, terrestrial acidification and water depletion. Steel from the landing gear is represented in orange colour and its impact is especially relevant in the metal depletion indicator. Finally, the contribution of the remaining components is not as significant.

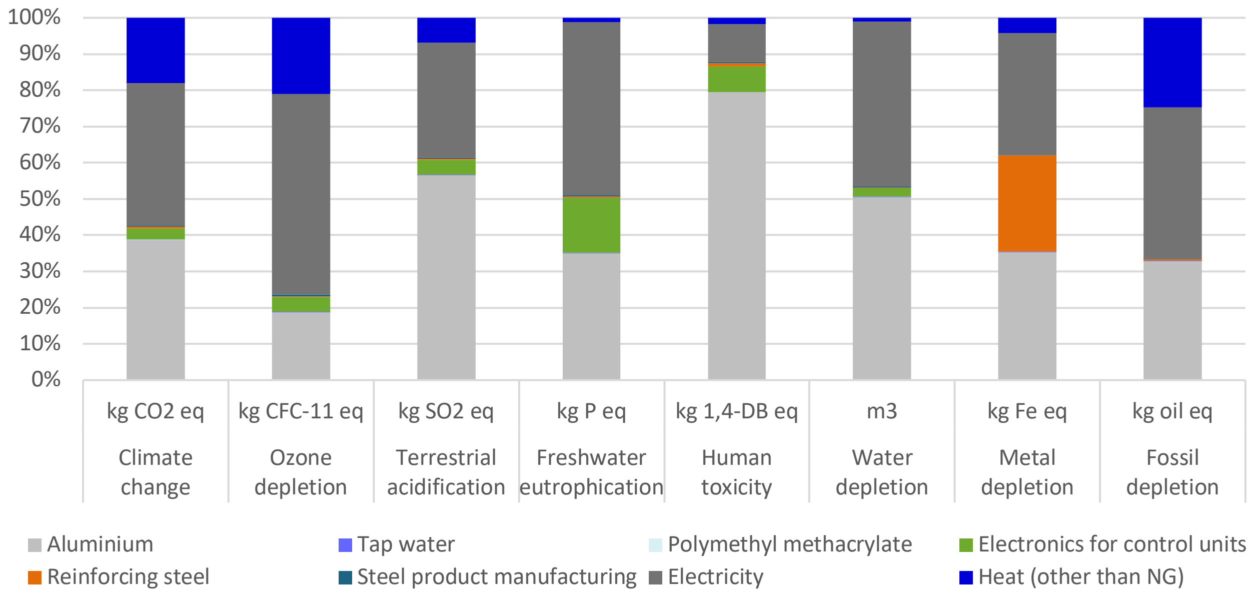


Figure 5-2: Relative environmental impact per indicator of a TECNAM 2006T aircraft in a MAV WADI unit

5.1.1.2 Multispectral camera

SpectroCam multispectral camera components impacts are shown in Figure 5-3. Regarding the manufacturing data from this camera, few details could be found, so the camera was divided into 3 parts following recommendations found in literature: glass lens, plastic and electronics, and the weight of each part is detailed in the LCI. After performing the environmental analysis of this camera, results revealed that electronics have the main impact on all the considered categories (from 80 % to 99 %). Ozone depletion is the only indicator in which the lens and the case amounts up to 20 % of the total environmental burden. In the remaining indicators, their contribution is lower than 10 %.

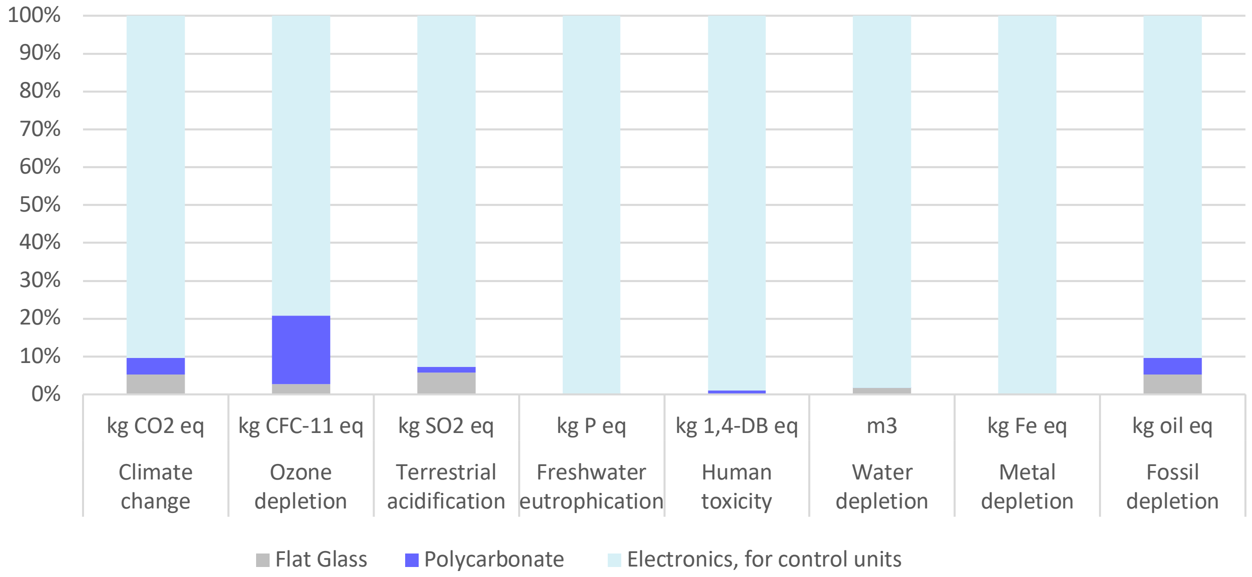


Figure 5-3: Relative environmental impact per indicator of the multispectral camera in a MAV WADI unit

5.1.1.3 *Infrared camera*

Noxcam IR camera components impacts are compiled in Figure 5-4. Among the impacts found in the LCA calculations, it is interesting to remark human toxicity indicator due to the presence of mercury in the IR detector. Mercury is responsible for almost the complete human toxicity impact on the IR camera and also, on the complete MAV unit. Looking into the remaining impact categories, most of the environmental burden is associated with the electronic system and the polycarbonate used for the case.

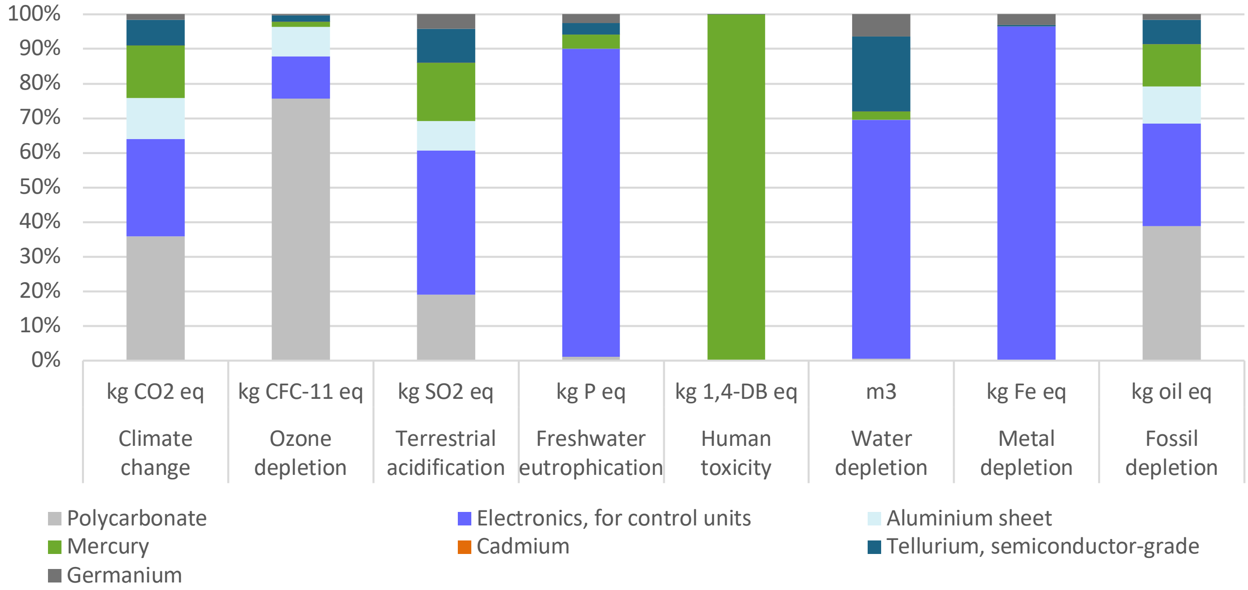


Figure 5-4: Relative environmental impact per indicator of the IR camera in a MAV WADI unit

In order to further analyse the impact contribution of the different camera components, Figure 5-5 depicts a network diagram to graphically see how each component impacts on the camera contribution to climate change impact, which is one of the three main impacts of this camera (see Table 5-1). This diagram shows that the plastic from the case is the main contributor to this impact (36.2 %), together with the electronics (28.0 %). Mercury, which impacts in a very important way to human toxicity, also represents 15.1 % of total climate change impact.

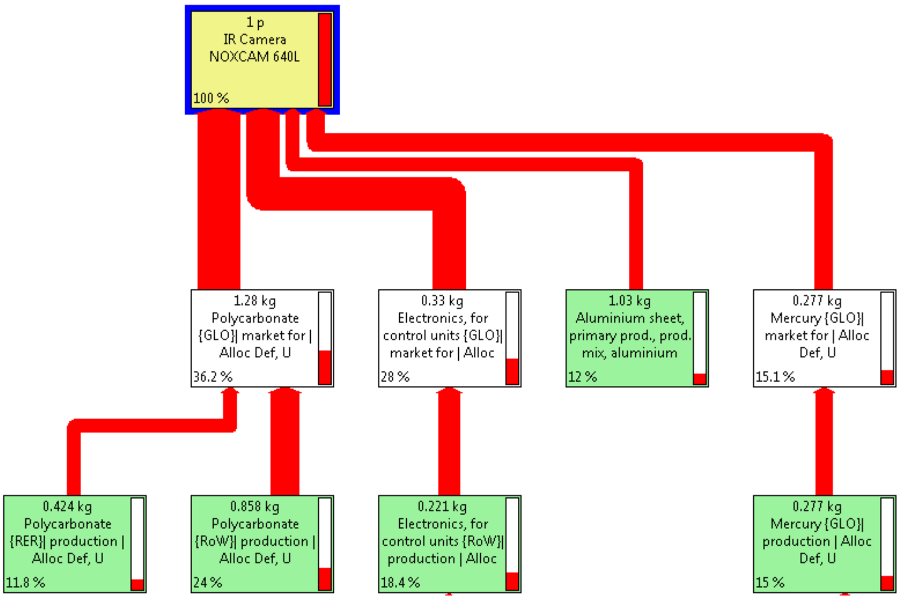


Figure 5-5: Network diagram for climate change impact in Noxcam IR camera

5.1.1.4 Inertial Measurement Unit (IMU) and Global Positioning System (GPS)

The next component by which the MAV WADI unit is composed is the Inertial Measurement Unit and Global Positioning system (IMU-GPS unit). This system is described in section **Errore. L'origine riferimento non è stata trovata.** and its relative impacts are shown in Figure 5-6. As no detailed information was available about its composition, it was considered to be formed by case and electronics. In all the considered environmental indicators, most of the impact is caused by electronics. The case, composed by polycarbonate, has its main impact contribution on the ozone depletion indicator, amounting 28 % of the total impact. Nevertheless, according to Table 5-1, ozone depletion is the smallest impact, so the contribution in absolute values is negligible.

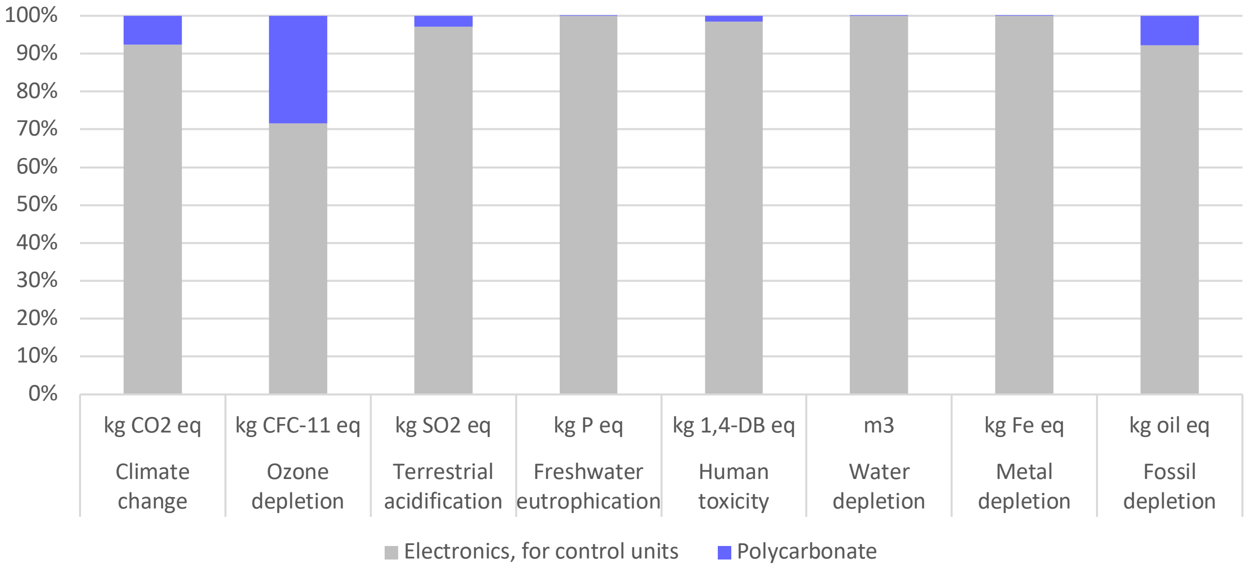


Figure 5-6: Relative environmental impact per indicator of the IMU-GPS system in a MAV WADI unit

5.1.1.5 Integration platform

The last component of the MAV WADI unit is the integration platform, whose purpose is to integrate all the components in the aircraft. Figure 5-7 shows the relative impact of its components. As it was previously stated, the platform is composed mainly of aluminium. Nevertheless, even though steel has a low weight, it has significant impact on many of the impact categories, such as water related categories and metal depletion. It is important to remark also the contribution of the cable mainly to freshwater eutrophication and human toxicity indicators.

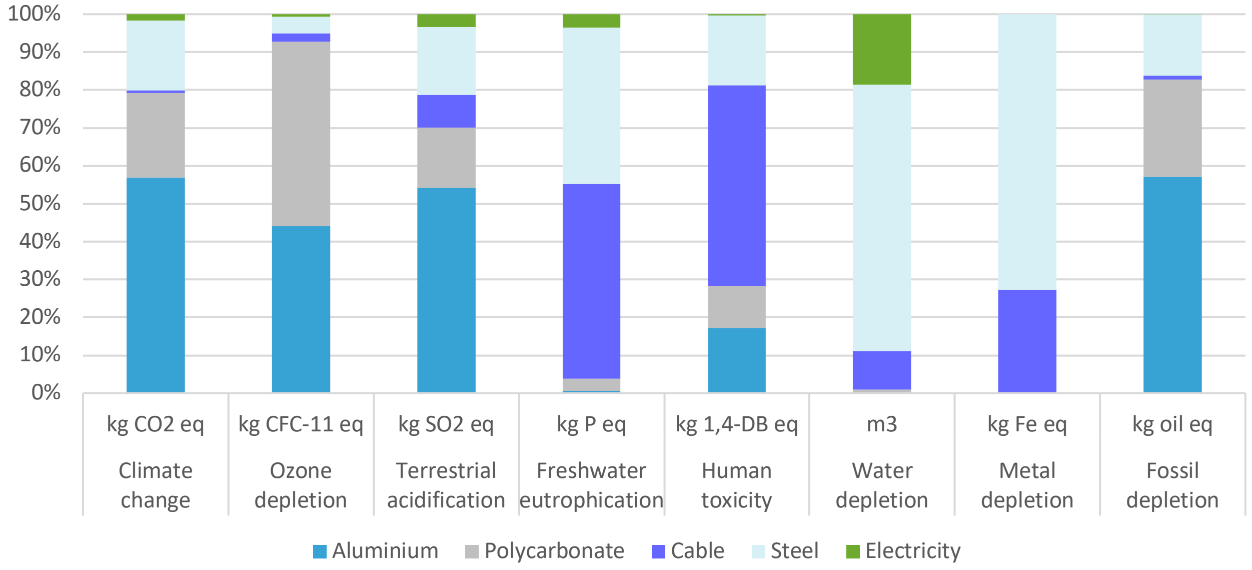


Figure 5-7: Relative environmental impact per indicator of the Integration Platform in a MAV WADI unit

5.1.2 MAV operation LCA

In order to complete the LCA of the MAV WADI unit, the operation stage must be also considered in the study. Under this perspective, all the resources consumed along the life cycle stages of the MAV must be identified and quantified by means of the environmental indicators previously defined. According to the LCI study, the most relevant consumption incurred in this stage is the aircraft fuel consumption. Besides, the lifetime of each MAV component must be taken into consideration since this will determine its durability and the periodicity with which they must be replaced (Table 4-7). On the other hand, the impacts associated with the end-of-life scenarios have been removed for the current study due to the fact that the partners found complicated to provide reliable quantitative information about the end-of-life strategies. Besides, the environmental burdens of this stage are not significant when the total life cycle is evaluated. In any case, a literature review of the most common end-of-life scenarios was carried out and it can be found in the Annex A of this deliverable.

In this light, a LCA has been performed considering all the life cycle stages from the cradle to the end of its use stage. Since the plane is the main component of the MAV unit, its lifespan was taken as reference (30 years and 400 h/year of effective operation). The results obtained are collected in Table 5-2. The orange column refers the total impact caused by the plane gasoline consumption for 30 years, and the green columns refer to the total impact of the components considering the number of times that they must be replaced in 30 years.

Table 5-2. Absolute environmental impact of the MAV components and the gasoline consumption (operation stage)

Impact Category	Units	Total	Gasoline	MAV TECNAM	Integration platform	Multispectral camera	IR Camera	IMU and GPS
Climate change	**kg CO_2 eq**	**270,471.37**	**247,317.02**	**23,025.30**	**14.79**	**45.75**	**39.32**	**29.17**
Ozone depletion	**kg CFC-11 eq**	**0.09**	**8.48E-02**	**1.78E-03**	**2.22E-06**	**3.59E-06**	**6.16E-06**	**2.59E-06**
Terrestrial acidification	**kg SO_2 eq**	**1,432.49**	**1,322.05**	**1.10E+02**	**6.07E-02**	**0.36**	**0.22**	**0.23**
Freshwater eutrophication	**kg P eq**	**28.18**	**13.62**	**14.31**	**2.90E-03**	**0.12**	**3.78E-02**	**8.25E-02**
Marine eutrophication	kg N eq	38.04	33.10	4.89	1.65E-03	2.19E-02	8.71E-03	1.39E-02
Human toxicity	**kg 1,4-DB eq**	**42,980.71**	**8,455.90**	**1,891.83**	**2.05**	**16.45**	**32,603.70**	**10.76**
Photochemical oxidant formation	kg NMVOC	1,659.41	1,519.75	1.39E+02	3.94E-02	0.24	0.13	0.15
Particulate matter formation	kg PM10 eq	421.43	378.10	4.30E+01	2.91E-02	0.13	8.36E-02	8.46E-02
Terrestrial ecotoxicity	kg 1,4-DB eq	21.16	12.61	2.07	5.48E-04	1.17E-02	6.42	7.62E-03
Freshwater ecotoxicity	kg 1,4-DB eq	160.22	156.61	2.65	1.09E-03	0.38	0.31	0.25
Marine ecotoxicity	kg 1,4-DB eq	233.63	185.28	9.67	1.59E-02	0.69	0.37	0.50
Ionising radiation	kBq U235 eq	81,137.46	74,544.12	6.58E+03	1.46	7.33	3.38	4.68
Agricultural land occupation	m^{2}a	797.37	524.80	2.70E+02	2.11E-02	0.85	0.85	0.49
Urban land occupation	m^{2}a	163.12	80.78	81.3	1.85E-02	0.50	0.18	0.32
Natural land transformation	m^2	0.88	0.53	0.34	1.06E-04	2.92E-03	1.02E-03	1.89E-03
Water depletion	**m^3**	**306,534.08**	**148,562.10**	**157,614.87**	**11.02**	**171.40**	**64.89**	**109.78**
Metal depletion	**kg Fe eq**	**1,354.12**	**893.58**	**360.21**	**2.98**	**50.53**	**13.91**	**32.89**
Fossil fuel depletion	**kg oil eq**	**443,745.81**	**437,606.94**	**6,104.42**	**3.60**	**12.56**	**10.23**	**8.03**

A set of indicators have been highlighted in the previous table and the relative impact of those components is depicted in Figure 5-8. In that figure, it can be seen at first glance that gasoline is the most contributing element in most of the environmental indicators. In fact, in some of them, **gasoline is responsible for more than 90 % of the total environmental impact caused by the MAV unit** (e.g. climate change: 91.4 %; ozone depletion: 97.9 %; fossil fuel depletion: 98.6 %). Consequently, the impacts associated with the MAV manufacturing are small on those indicators and most of the life cycle impacts are caused during the operation stage. On the other hand, **multispectral cameras have a significant impact on the human toxicity indicator** (75.8 %), mainly due to the **mercury** existing in one of their components, as it was widely explained in the LCA of the MAV manufacturing. Finally, it is also significant the weight of the **TECNAM P2006T plane** on the **freshwater eutrophication** (50.8 %) and the

water depletion indicator (51.4 %). Even though the huge environmental impact of the plane in comparison to the rest of the MAV components, its lifetime is much longer and its total environmental impact can be shared among more hours of operation. Besides, from a life cycle perspective, the gasoline consumption impact is bigger in most of the selected indicators.

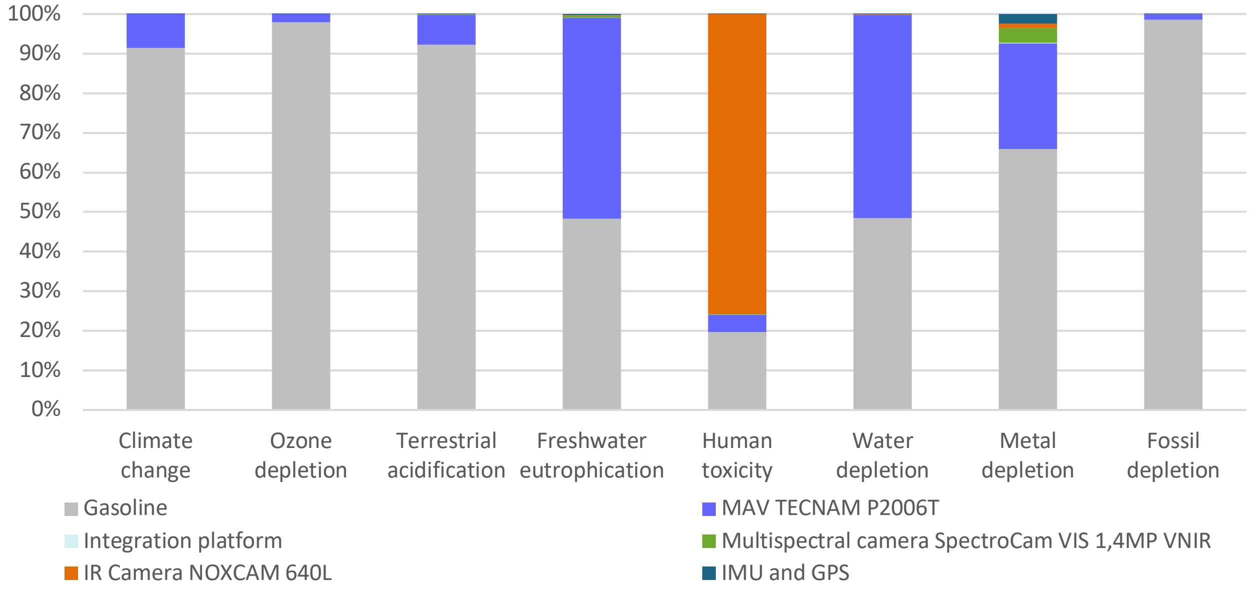


Figure 5-8. Relative environmental impact per indicator of the MAV WADI unit

5.2 Unmanned Aircraft Vehicle (UAV) LCA

5.2.1 MAV manufacturing LCA

Once finished the LCA of manufacturing one unit of MAV, the second technology developed in the WADI project is the UAV. The UAV WADI unit is composed of three main elements: the drone (model GG-X4), the IR camera and the multispectral camera. Table 5-3 contains the LCA impact results, in absolute values, for all the impact categories analysed by the calculation method (ReCiPe Midpoint (H)). Again, the categories selected to be analysed in more detail are marked in bold: climate change, ozone depletion, terrestrial acidification, fresh water eutrophication, human toxicity, water depletion, metal depletion and fossil depletion.

Table 5-3: Environmental impact of one unit UAV manufacture

Impact category	Unit	Total	UAV GG-X4	IR camera FLIR Vue Pro R	Multispectral camera Micasense RedEdge 3
Climate change	**kg CO_2 eq**	**45.59**	**43.22**	**0.68**	**1.69**
Ozone depletion	**kg CFC-11 eq**	**3.84E-06**	**3.58E-06**	**1.20E-07**	**1.35E-07**
Terrestrial acidification	**kg SO_2 eq**	**0.44**	**0.42**	**4.83E-03**	**1.38E-02**
Freshwater eutrophication	**kg P eq**	**0.15**	**0.14**	**7.26E-04**	**4.78E-03**
Marine eutrophication	kg N eq	2.86E-02	2.75E-02	3.20E-04	8.30E-04
Human toxicity	**kg 1,4-DB eq**	**38.57**	**37.70**	**0.19**	**0.68**
Photochemical oxidant formation	kg NMVOC	0.23	0.22	3.79E-03	9.02E-03
Particulate matter formation	kg PM10 eq	0.15	0.14	2.12E-03	5.05E-03
Terrestrial ecotoxicity	kg 1,4-DB eq	1.01E-02	9.58E-03	8.39E-05	4.47E-04

Freshwater ecotoxicity	kg 1,4-DB eq	0.35	0.34	1.82E-03	1.44E-02
Marine ecotoxicity	kg 1,4-DB eq	0.84	0.81	4.13E-03	2.62E-02
Ionising radiation	kBq U235 eq	6.66	6.33	5.60E-02	0.27
Agricultural land occupation	m²a	0.69	0.65	6.88E-03	3.17E-02
Urban land occupation	m²a	0.53	0.50	1.41E-02	1.89E-02
Natural land transformation	m²	2.54E-03	2.38E-03	5.42E-05	1.09E-04
Water depletion	**m³**	**183.74**	**176.02**	**1.32**	**6.39**
Metal depletion	**kg Fe eq**	**76.37**	**74.14**	**0.32**	**1.92**
Fossil depletion	**kg oil eq**	**13.87**	**13.22**	**0.18**	**0.47**

In order to further analyse where these impacts come from, Figure 5-9 depicts the relative contributions of the elements which are part of the UAV WADI unit. In this case, results show that the **main contribution**, again, comes from the **aircraft** (drone) **and** that the **multispectral camera** has greater impact than the IR device. Unlike the relative environmental impact of the MAV unit (Figure 5-1), the IR camera does not have a significant contribution in the human toxicity indicator, mainly because in this unit, there is not mercury in the IR detector.

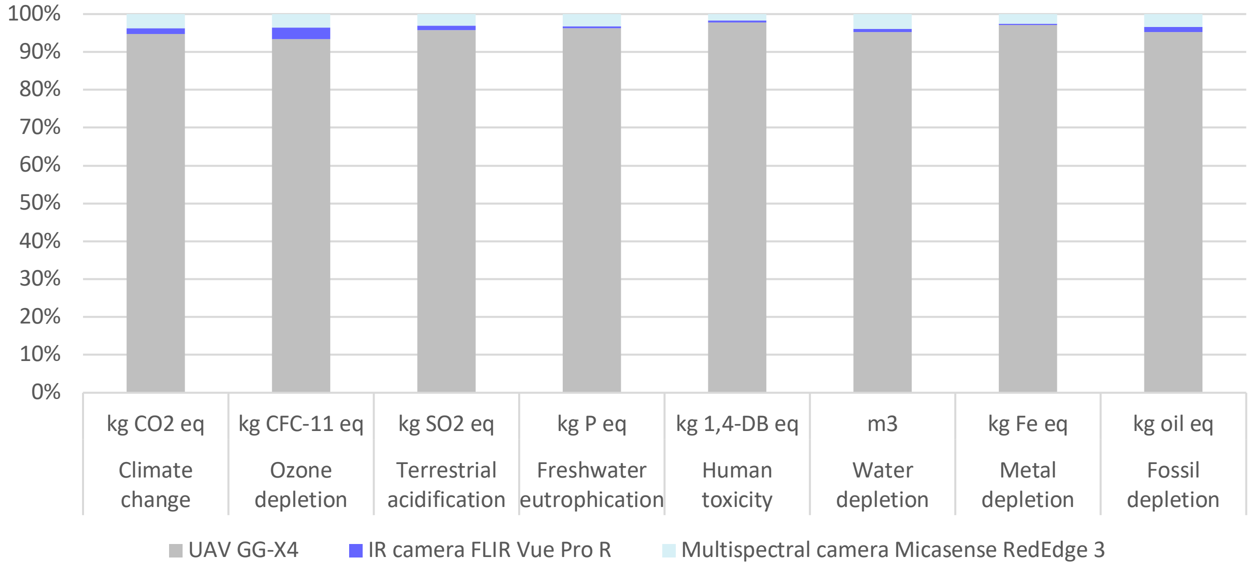


Figure 5-9: Relative environmental impact per indicator of a UAV WADI unit

5.2.1.1 UAV GG-X4 drone

The drone used in the UAV unit is mainly formed by carbon fibre, as well as other electronic components. Figure 5-10 shown the relative environmental impact for the eight selected impact indicators divided by all the components of the drone. **Electronic** components and the **battery cells** have the main impact for all the categories. Its influence is especially significant in some indicators such as **freshwater eutrophication or water depletion**, where its **contribution is greater than 90 %** of the total environmental burden associated with the complete drone. Regarding the **carbon fibre**, it mainly impacts on **carbon footprint and fossil depletion** (about 20 and 30 % respectively of the total drone impact).

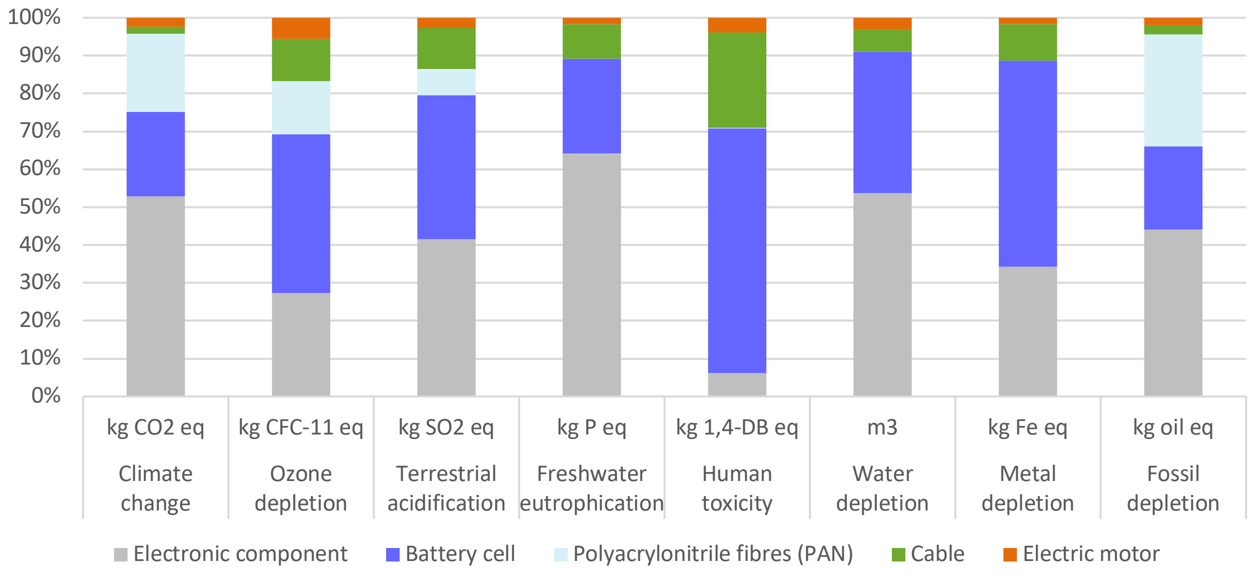


Figure 5-10: Relative environmental impact per indicator of the drone in a UAV WADI unit

5.2.1.2 Multispectral camera

The Micasense multispectral camera was considered to be formed by glass (lens), polycarbonate (case), cable and electronics. The weight fraction of each component was considered the same as in the MAV multispectral camera. Figure 5-11 depicts relative contributions of each material to the selected impact categories. As for the cameras analysed in the MAV unit, electronics represent the main contributor to all the environmental impacts of this camera. In all cases, **the relative weight of electronics is greater than 80 %.**

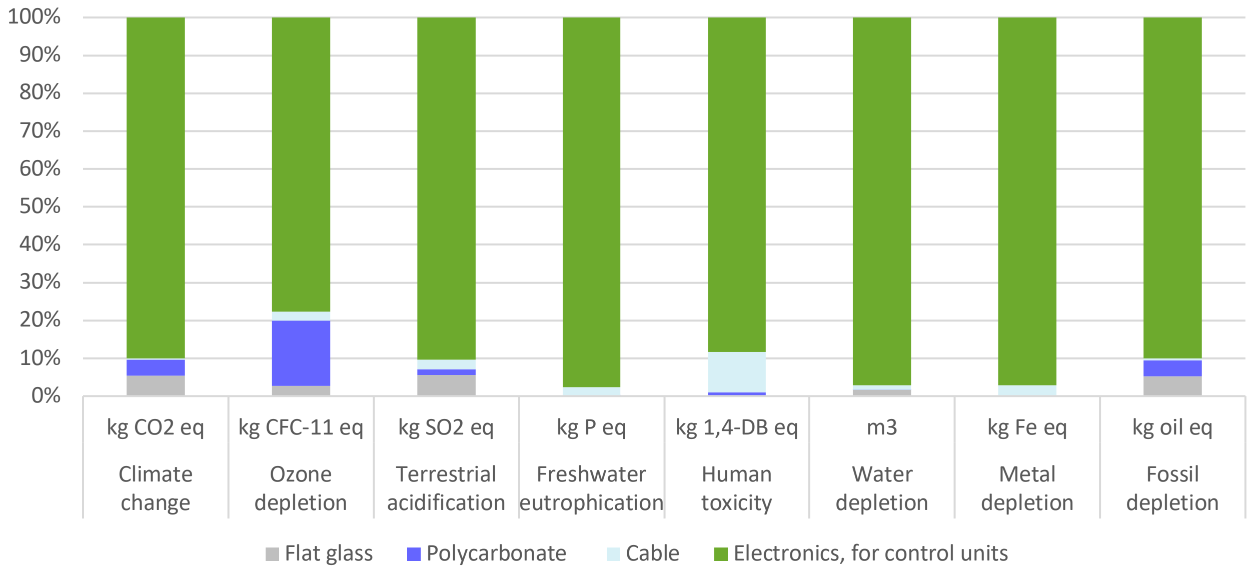


Figure 5-11: Relative environmental impact per indicator of the multispectral camera in a UAV WADI unit

5.2.1.3 Infrared camera

Regarding the IR camera used in the UAV unit, all its components were estimated from information available in the technical specifications document of the camera. In this camera, there is not mercury among its components and therefore, the value of the human toxicity indicator is much lower than for the IR camera of the MAV unit. Besides, since it was not possible to find the environmental burdens of using vanadium in the available databases, it was taken cobalt as substitute (see the explanations given in the LCI description). As human toxicity was the main impact category on which MAV IR camera had impact (see Table 5-1), vanadium oxide and cobalt effects on humans were compared and seen to be similar (related to carcinogenic impacts) [21]. Regarding the rest of the IR camera parts, it was considered that their weight is proportional to those of the IR camera in the MAV (lens, plastic, IR element, electronics, etc.).

Relative environmental impacts are shown in Figure 5-12 for the UAV IR camera. This graph reveals that polycarbonate from the camera case has its main impact on ozone depletion, climate change and fossil depletion indicators, while electronics is shown to be more important in fresh water eutrophication and water and metal depletion. On the other hand, cable has an important impact on human toxicity and cobalt impact is more balanced among all the considered categories.

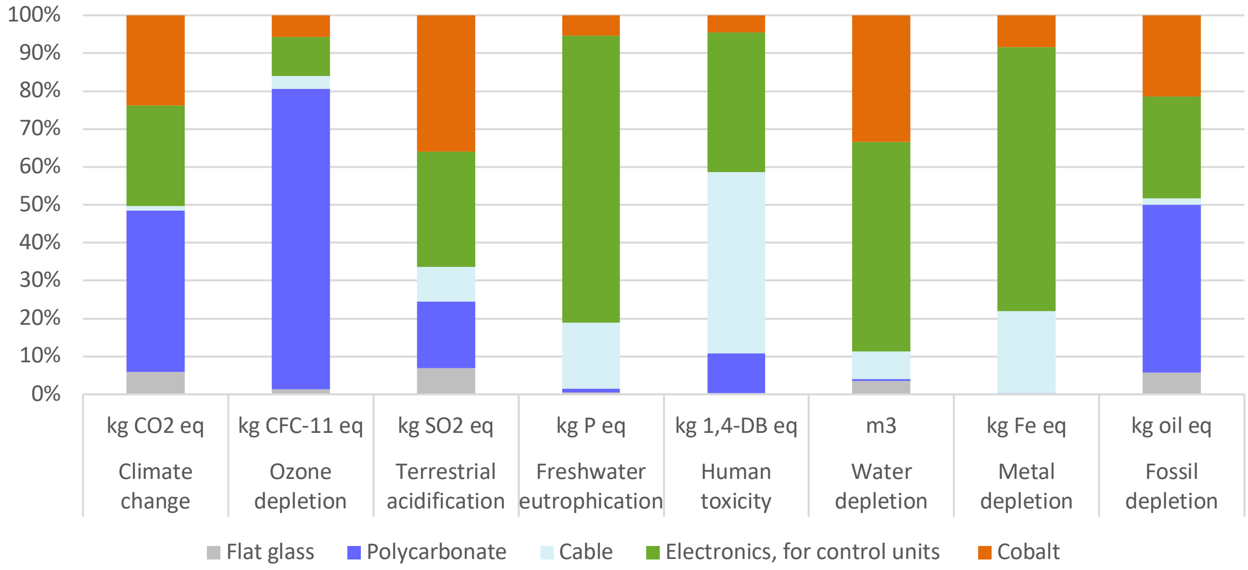


Figure 5-12: Relative environmental impact per indicator of the IR camera in a UAV WADI unit

5.2.2 UAV operation LCA

During the LCA of the manufacturing stage, the environmental burdens associated with all the components of the UAV were quantify but without considering the durability of each one and how many times they must be replaced along the lifetime of the drone. For this reason, even though the impact of some parts can look small, if they must be replaced frequently, its total impact on the full life cycle can be significant.

In order to address this gap, the operation stage must be included in the analysis boundaries. Under this perspective, the analysis is closer to cover all the stages of the life cycle of the product. As mentioned in the boundaries description section, the end-of-life stage should be also included in the LCA if a real "cradle-to-grave" perspective wanted to be performed. However, since the impact associated with that stage is normally small in comparison to the rest of the life cycle stages, and besides, due to the complex process of estimating the life cycle strategies of an innovative product, the end-of-life scenarios impacts were not qualitatively determined. However, a description of the most common practices is included in the Annex A of this deliverable.

Coming back to the analysis of the operation stage, the lifetime of each component, and the equivalent units consumed in 5 years, which is the lifetime of the drone structure and the reference unit for this analysis, can be found in Table 4-13. Besides, the total electricity consumption of the drone batteries is collected in Table 4-14. Depending on the country where the electricity is generated, the environmental impacts associated with its generation can considerably vary. In this case, the flights were performed in France and Portugal and thus, different scenarios have been performed for each scenario. Besides, the average electricity mix of EU-28 has been considered to check the representativeness of the mentioned countries in the European electricity production.

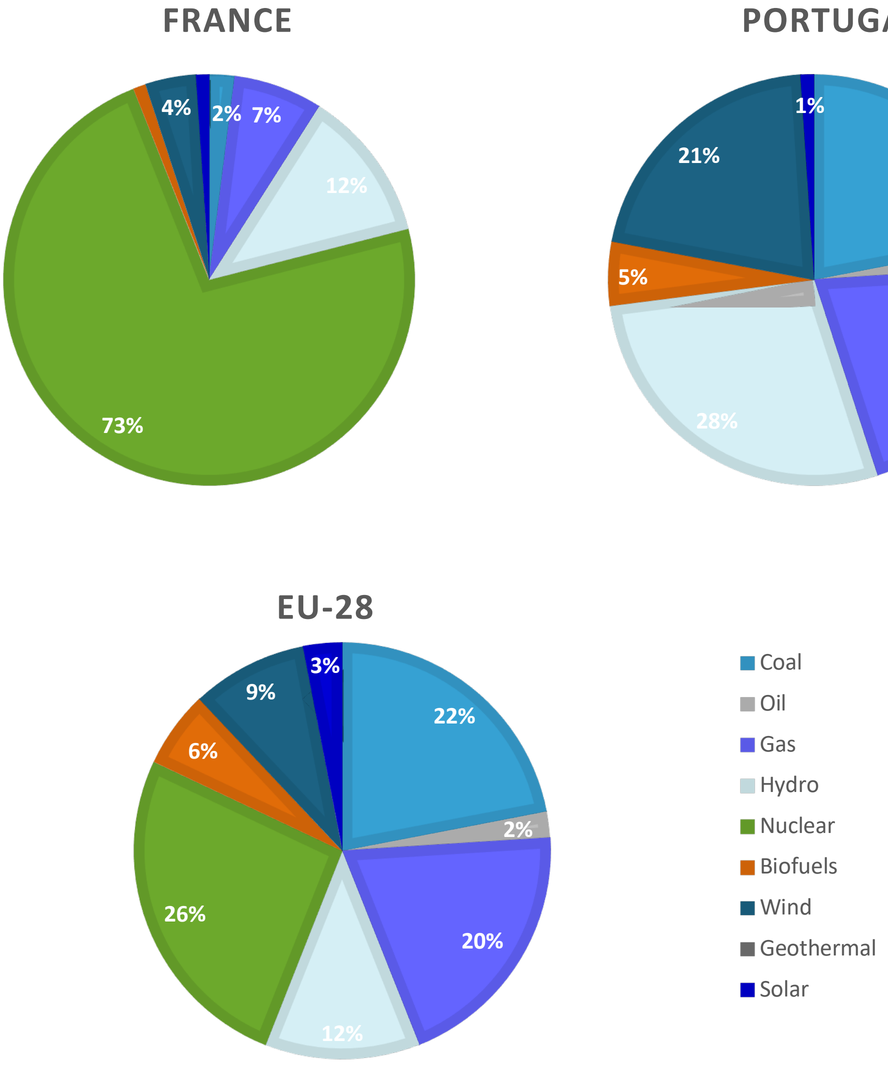


Figure 5-13. Electricity mix of France, Portugal and the average mix of EU-28

At first glance, it can be seen that in France, most of the energy is generated from nuclear sources (73 %). In Portugal, there are four main actors in the electricity mix: hydro-energy (28 %), coal (22 %), wind energy (21 %) and natural gas (21 %). Finally, the average electricity mix of EU-28 shows a distribution that could be understood as a combination of the previous mixes. The importance of the renewables energies is, in general, higher than in France, and the dependence of fossil fuels, such as natural gas, lower than in Portugal. The huge differences in these electricity mixes will cause big variations in the results and in the LCA conclusions.

The results obtained in the LCA of the UAV can be found in Table 5-4. On one hand, the green columns contain the impact caused by each component taken into account its lifetime and the periodicity with which they must be replaced. On the other hand, the orange columns contain the impact caused by the electricity consumption if the Portuguese o French electricity mix is considered.

Table 5-4. Absolute environmental impact of the UAV components and its electricity consumption (operation stage)

Impact Category	Units	UAV GG-X4 s/bat s/eng	Multispectral camera Micasense RedEdge 3	IR camera FLIR Vue Pro R	Battery drone	Engine drone	Electricity, Portugal	Electricity, France
Climate change	**kg CO_2 eq**	**32.57**	**0.85**	**0.34**	**226.00**	**1.99**	**283.42**	**56.75**
Ozone depletion	**kg CFC-11 eq**	**1.88E-06**	**6.75E-08**	**5.99E-08**	**3.52E-05**	**3.95E-07**	**5.79E-07**	**5.06E-05**
Terrestrial acidification	**kg SO_2 eq**	**0.25**	**0.01**	**2.42E-03**	**3.73**	**0.02**	**1.92**	**0.25**
Freshwater eutrophication	**kg P eq**	**0.10**	**2.39E-03**	**3.63E-04**	**0.83**	**4.56E-03**	**0.11**	**1.00E-02**
Marine eutrophication	kg N eq	1.72E-02	4.15E-04	1.60E-04	0.23	1.21E-03	5.11E-02	1.06E-02
Human toxicity	**kg 1,4-DB eq**	**11.93**	**0.34**	**0.10**	**569.19**	**2.89**	**1.91**	**7.10**
Photochemical oxidant formation	kg NMVOC	0.16	4.51E-03	1.89E-03	1.32	0.01	0.86	0.15
Particulate matter formation	kg PM10 eq	0.09	2.52E-03	1.06E-03	1.25	0.01	0.51	0.10
Terrestrial ecotoxicity	kg 1,4-DB eq	3.66E-03	2.24E-04	4.19E-05	0.13	7.98E-04	2.57E-03	1.34E-02
Freshwater ecotoxicity	kg 1,4-DB eq	0.32	0.01	9.10E-04	0.21	0.01	1.33E-03	1.35E-02
Marine ecotoxicity	kg 1,4-DB eq	0.54	0.01	2.06E-03	6.05	0.03	0.02	0.07
Ionising radiation	kBq U235 eq	5.26	0.14	0.03	22.41	0.23	2.56	439.42
Agricultural land occupation	m^2a	0.47	0.02	3.44E-03	3.47	0.05	0.23	1.80
Urban land occupation	m^2a	0.34	9.45E-03	7.03E-03	3.25	0.03	2.04	0.24
Natural land transformation	m^2	1.65E-03	5.44E-05	2.71E-05	1.31E-02	3.37E-04	1.34E-02	1.57E-03
Water depletion	**m^3**	**104.44**	**3.20**	**0.66**	**1,540.10**	**11.52**	**5,636.63**	**2,291.40**
Metal depletion	**kg Fe eq**	**32.56**	**0.96**	**0.16**	**943.24**	**2.54**	**0.14**	**3.71**
Fossil depletion	**kg oil eq**	**10.04**	**0.23**	**0.09**	**68.08**	**0.54**	**59.86**	**16.31**

As a summary of the total environmental impact caused by the UAV both in Portugal and in France can be found in Table 5-5. As it was done in the previous sections, some indicators have been highlighted as the more representative ones and they have been studied with more detail. In fact, the relative impact of the UAV depending on the electricity mix considered is graphically depicted in Figure 5-14 for the selected indicators.

Table 5-5. Total environmental impact of the UAV considered the Portuguese and French electricity mix

Impact Category	**Unit**	**Total Impact Portugal**	**Total Impact France**
Climate change	**kg CO_2 eq**	**545.16**	**318.49**
Ozone depletion	**kg CFC-11 eq**	**3.82E-05**	**8.82E-05**
Terrestrial acidification	**kg SO_2 eq**	**5.93**	**4.26**
Freshwater eutrophication	**kg P eq**	**1.05**	**0.95**
Marine eutrophication	kg N eq	0.30	0.26
Human toxicity	**kg 1,4-DB eq**	**586.35**	**591.54**
Photochemical oxidant formation	kg NMVOC	2.36	1.65
Particulate matter formation	kg PM10 eq	1.86	1.45
Terrestrial ecotoxicity	kg 1,4-DB eq	0.14	0.15
Freshwater ecotoxicity	kg 1,4-DB eq	0.55	0.56
Marine ecotoxicity	kg 1,4-DB eq	6.66	6.71
Ionising radiation	kBq U235 eq	30.62	467.48
Agricultural land occupation	m^{2}a	4.25	5.81
Urban land occupation	m^{2}a	5.68	3.87
Natural land transformation	m^2	0.03	0.02
Water depletion	**m^3**	**7,296.55**	**3,951.32**
Metal depletion	**kg Fe eq**	**979.59**	**983.17**
Fossil depletion	**kg oil eq**	**138.84**	**95.29**

As expected, the value of the ionizing radiation indicator is much greater in France than in Portugal due to the big weight of the nuclear sources in the French electricity mix. In fact, looking at the Figure 5-15, it is possible to check that most of the total ionizing radiation impact in France is caused by the electricity consumption, whereas in Portugal, the influence of the electricity in that indicator is almost negligible. Something similar is found in the ozone depletion indicator although the difference is not so substantial. The value of this indicator is much bigger in France than in Portugal and this is because the contribution of the French electricity to this indicator is significant and in Portugal, is lower than 5 %.

On the other hand, the electricity mix of Portugal has a big proportion of fossil fuel sources such as coal or natural gas. For this reason, the impact of the UAV in the climate change indicator when is used in Portugal is almost twice than the impact in France. A similar proportion between the French and the Portuguese impacts can be found in the metal depletion and fossil fuel depletion indicators.

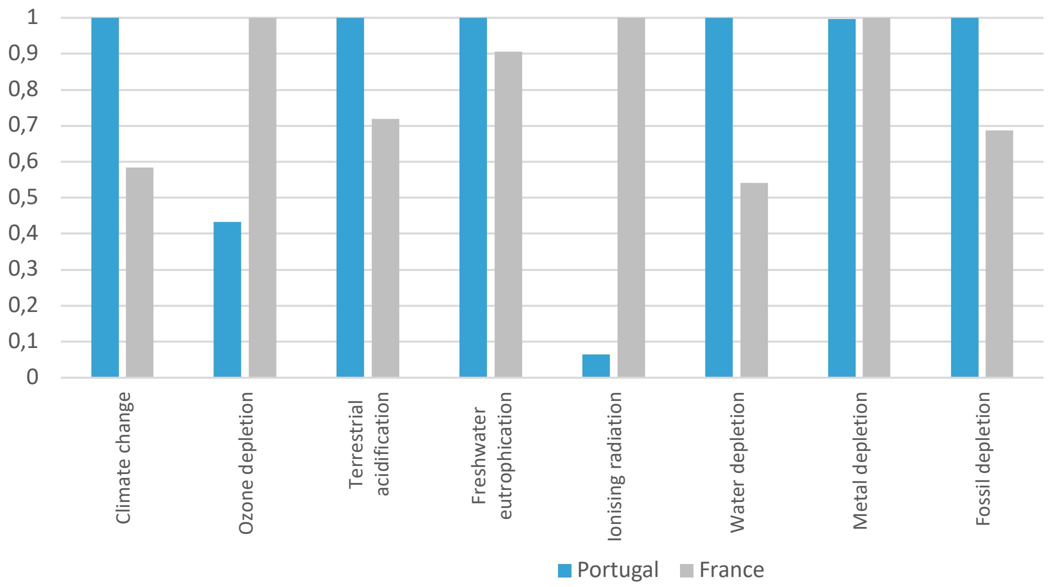


Figure 5-14. Relative impact of the UAV if the electricity mix of Portugal or France is considered

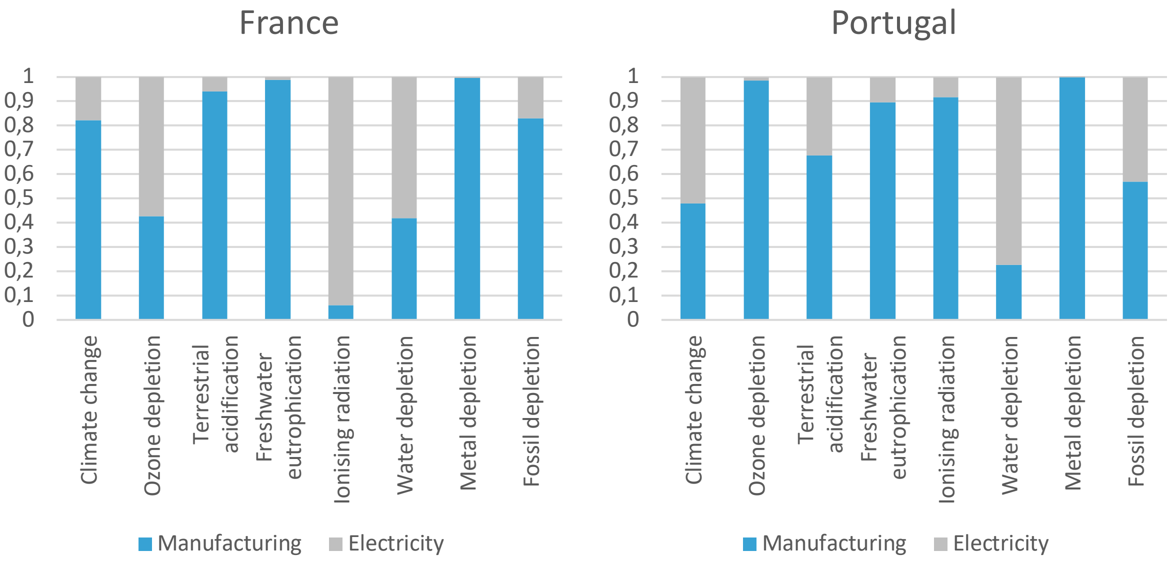


Figure 5-15. Contribution of the UAV components and the batteries electricity consumption to the total environmental impact of the UAV

To sum up, **the electricity consumption originates most of the total environmental impact on many indicators**. When this happens, it is very important to stablish the electricity mix that is going to be used for the LCA, because it can strongly change the conclusions.

Finally, the last part of the UAV operation LCA is dedicated to determining the effect of considering the lifetime of each component on the total environmental impact. To this end, Figure 5-16 and Figure 5-17 contains the total relative impact of the UAV WADI unit with the Portuguese and French electricity mix respectively.

In both cases, in most of the indicators, the greatest contributor is the drone batteries impact. This result can be surprising if it is compared to the results obtained during the UAV manufacturing LCA, where the relative contribution of the batteries was low. However, in that case, it was considered that the UAV was using only one battery. Now, when we take into account the lifetime and the replacement period of the batteries, the number of batteries that must be used along the lifetime of the drone are 34 (see LCI section), increasing its environmental burden. Besides, the electricity consumption of the batteries has a relevant weight on the climate change indicator (especially in Portugal), water depletion and fossil fuel depletion indicators. Finally, the contribution of the general structure is also relevant for some indicators but always lower than 10 %.

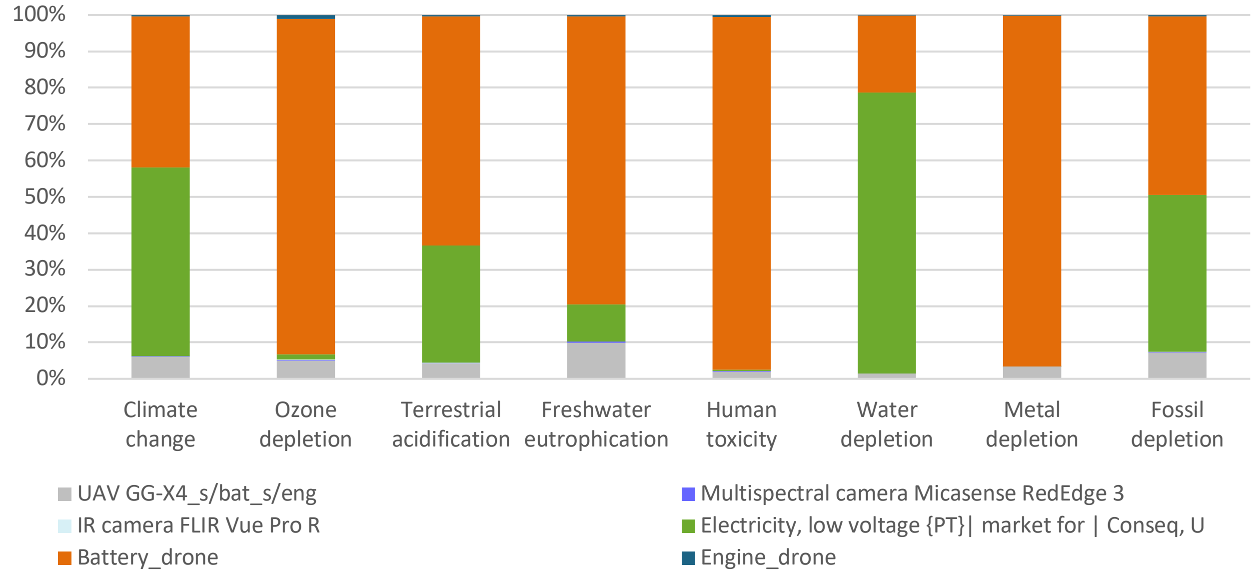


Figure 5-16. Relative environmental impact per indicator of the UAV WADI unit considering the Portuguese electricity mix

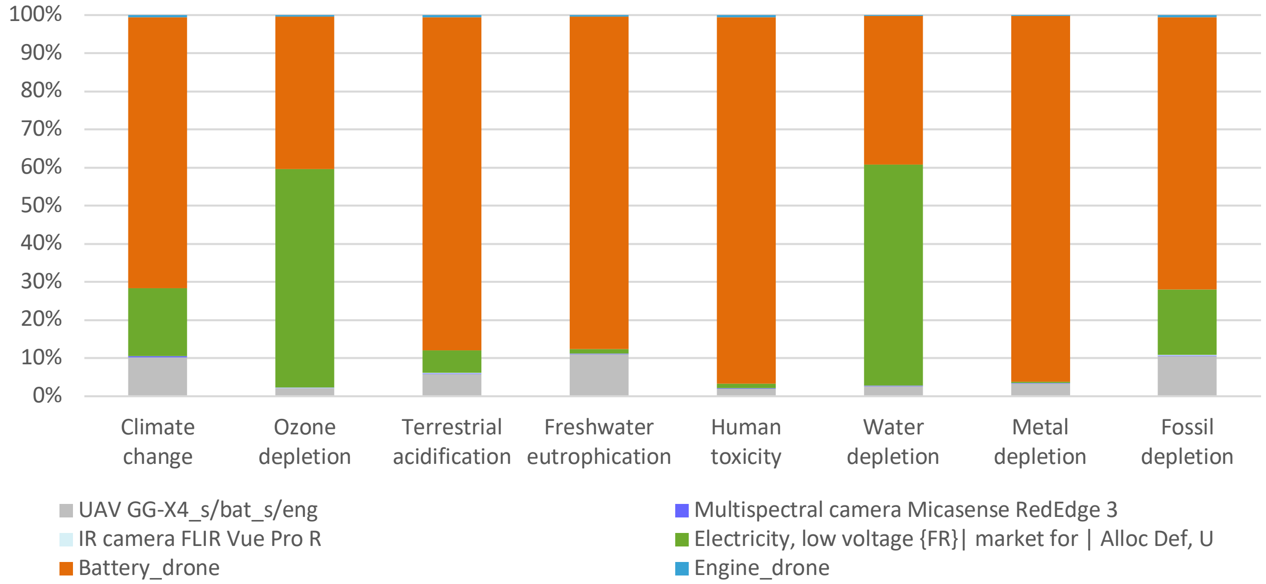


Figure 5-17. Relative environmental impact per indicator of the UAV WADI unit considering the French electricity mix

6 Environmental benefits associated with water leaks detection

Once performed the LCA of both WADI units, this section aims at performing a comparison between the environmental burdens caused by the manufacturing and use of the MAV and UAV units with the potential benefits derived from its application.

In order to quantify the potential benefits of this innovative leakage detection technique, the assumptions used in the deliverable 9.1 – "Analysis of Market Conditions" are used. In that report, it was considered that the WADI service could be implemented over five percent of the total European water supply network. Under this scenario, the implementation of the WADI service could recover 91.25 mill m^3/year of drinking water. Regarding irrigated water, if the WADI service were applied over 5 % of the total irrigated area, the total water saved could potentially be 225 mill m^3/year.

If the previous water savings are compared to the water depletion associated with the life cycle stages of the WADI units, the benefits associated with this detection system are huge. On the one hand, the water footprint of the MAV unit during its complete lifetime (30 years) is about 300,000 m^3 (10,000 m^3/year). Even though this is the water depletion caused but only one MAV WADI unit, and the previous potential water saving was estimated considering than many WADI units are working at the same time, the difference is so high that in all the cases, important benefits will be obtained.

On the other hand, the water depletion of the UAV unit caused by its manufacturing and by the consumptions incurred along its use stage (5 years) is much lower. In fact, taking into account the Portuguese electricity mix to quantify the impacts caused by the drone electric consumption, the total water footprint of the UAV WADI unit is about 7,300 m^3 (1,460 m^3/year). In comparison to the potential benefits achieved by the WADI techniques, this value is almost negligible. The water leaks detection capacity of the UAV unit is lower than the MAV unit because of the limited autonomy of the batteries and the covered area per flight. However, this unit will be a useful detection method to explore areas with complicated access for other alternatives and therefore, both methods complement each other.

From the CO_2 emissions point of view, it was estimated in D9.1 that the WADI service could potentially reduce 116.14 mill kg of CO_2/year by reducing the energy consumption for the water supplying. In comparison to the total carbon footprint associated with the MAV and UAV WADI units (270,471 kg CO_2 and 545 kg CO_2 respectively), the benefits are enormous.

To sum up, the preliminary environmental evaluation performed for the WADI units indicates that the benefits achieved are much greater than the burdens caused by their use and their manufacturing processes. However, the flights performed during the WADI project in real validation pilot sites (WP5 and WP6) will determine the real potential of water leaks detection for both the MAV and UAV units. Those results will allow to adjust the benefits associated with this innovative technology and then, to verify if the estimations made are in concordance with the real detection potential of the WADI systems.

7 Other leak detection methods

As already mentioned in Deliverable D2.1. Report on state-of-the-art, end user requirements, demonstration scenarios and risk analysis, there are other techniques applied for the detection of water leaks in large transport networks considered in this analysis such as:

- Ground-based Acoustic methods (most traditional technique for leak detection),
- Ground-based Inline methods (highest-performing technique on transmission mains),
- Satellite-based SAR (main potential competitor for WADI)

The results obtained from the Life Cycle Analysis (LCA) with the WADI methodology will be compared with those obtained through traditional acoustic detection as it is the most common and probably the easiest to use, carried out in parallel in the same infrastructure, to assess the success of innovation.

The following section analyses the terrestrial acoustic methodology used and performs LCA that will allow comparison of the environmental impacts of the different WADI techniques analyzed (MAV and UAV) from the perspective of the use of environmental resources and emissions.

The main objective of this LCA is therefore to achieve a comparative assessment of the WADI solution with a typical ground leak detection (acoustic) technique.

7.1 Terrestrial acoustic methods

Historically, acoustic leak detection is the most usual method applied for identifying leaks on water pipelines, as the first acoustic correlator was developed back in the early 1960s. Acoustic methods are based on the fact that pressurized water passing through a leak emits soundwaves that travel through the walls of the pipe, the surrounding ground and along the fluid flowing into the pipe. These soundwaves can be detected and amplified by electronic translators (i.e.amplifiers).

7.1.1 Scope of application

Acoustic methods are mainly dedicated to pressurized piping systems, with best performances obtained at high pressures, metallic pipes and environments with low background noise.

Based on the tests of Huchs and Richle (1991), for some favorable conditions, leaks with discharges as small as 0.05m^3/hour could been located using acoustic correlation.

7.1.2 Technical specifications

Acoustic leak detection is a dynamic process which requires qualified personnel and involves the use of various technologies and procedures. In large transmission mains, once the existence of a water loss has been confirmed (i.e. the outflow from the system is lower than the inflow), acoustic leak detection normally develops in three phases:

1. Direct Sounding of the contact points using the electroacoustic listening stick
2. Acoustic correlation to detect spot and localized leaks
3. Surface Sounding (indirect method) to confirm leak position ground microphone.

Each phase involves the use of the instrumentation described below:

- **Electroacoustic listening Stick**

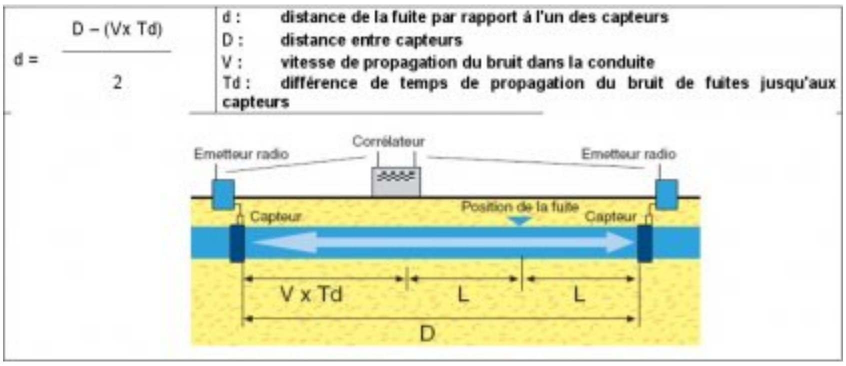
Not all leaks produce an audible noise to the human ear. For this reason, an electroacoustic listening rod is used to amplify, filter and transmit the noise generated by water that escaping from buried pipes under pressure to the operator's headphones.

Electroacoustic listening sticks are applied at the contact points of the pipe (e.g. wherever the pipe can be physically touched: valves, washouts, hydrants, sections of pipe above ground level, etc.) to check if a leak is occurring nearby (as far as the sound propagates along the pipe wall). However, owing to the lack of contact points on trunk mains, and the short sound propagation distance of large diameter pipes, Direct Sounding with listening rod is rarely done on large water mains.

Figure 7-1. AQUAPHON AF100 electroacoustic listening stick

- **Acoustic Correlator**

The acoustic correlation technique is, nowadays, the most accurate technique in leak detection and basically consists of analyzing in detail the sound that produces a leak in a conduction through two sensors that capture the sound either in direct contact with the fluid, or in contact with the pipes that drive it. Once the signal is picked up by the sensors, it is sent to the central unit of the equipment, where it is processed, accurately determining the signal strength and indicating the distance of the leak regarding both sensors. Therefore, the exact location of a leak is being reflected on the computer screen as a measurement of the time it takes for the sound to reach both sensors. Thus, acoustic correlation with direct sensor and acoustic correlation with indirect sensor can be distinguished.



$$d = \frac{D - (V \times Td)}{2}$$

d : distance de la fuite par rapport à l'un des capteurs
D : distance entre capteurs
V : vitesse de propagation du bruit dans la conduite
Td : différence de temps de propagation du bruit de fuites jusqu'aux capteurs

Figure 7-2. Scheme. Principle of correlation technique

The devices based on this method are of multipurpose type applicable to all types of pipes, whether they are cast iron, steel, fibrocement, reinforced concrete, polyethylene or PVC.

In general, these devices are basically composed of a Central Unit and two *accelerometers or hidrophones*. The equipment is complemented by a radio transmission system, from the signal picked up by the sensors, to the Central Unit for processing. The equipment also consists of headphones, magnetic and pressure adapters.

Figure 7-3. Acoustic correlator model AQUASCAN TM2

- **Listening Sticks and Ground Microphones**

The ground microphone is based on the same principle of an electroacoustic listening stick, with the difference that the instrument is not applied directly to the contact points to detect sound propagation along the pipe wall, but on the ground surface above the buried pipe (to detect sound propagation through the ground), so it is known as an *Indirect Sounding Technique*.

The microphone is the fundamental pillar for its effectiveness and simplicity. It consists of a receiver that transmits sound and is subsequently amplified and filtered by electronic systems.

The sound collector consists of a high-sensitivity microphone, placed on a probe whose mission is to isolate the piezoelectric sensor from ambient sounds that could impair detection.

The extreme sensitivity of the sensor allows to differentiate small variations in the signal strength, imperceptible by the human ear. In electronic models, these variations are represented both graphically and numerically on an LCD screen. The signal strength can be continuously compared using the progressive memory function.

Figure 7-4. Ground acoustic microphone

In general, all systems and devices used for leak detection are based on the physical fact that, by escaping pressure water from the leak, a sound vibration is generated and picked up. Ground microphones are particularly useful for confirming the precise location of a leak following a correlation and before digging for repair.

7.2 LCI of Acoustic Equipment

The next step is to develop the Inventory of Materials, Energy and Emissions for the Life Cycle Assessment of the different components and materials acoustic equipment. For this purpose, the inputs and outputs of the components of the technical equipment shall be determined.

Given the wide range of acoustic models currently available on the market (with sensors, ultrasound, GPS, etc.) it was decided to select the most representative according to their manageability and frequency of use. The following data obtained are based on the data sheets of the selected devices.

7.2.1 Acoustic Equipment manufacturing LCI:

To perform the analysis, the next step is to elaborate an inventory of the different components and materials required to manufacture each terrestrial acoustic equipment.

In the following attached tables, the composition of each individual element is defined, and technical specifications of the equipment itself.

Table 7-1. Technical characteristics and components of Electroacoustic listening rod

EQUIPMENT CONFIGURATION: ELECTROACOUSTIC LISTENING ROD				
Elements	Composition	Dimensions	Weight	Percentages
1 receiver	Electronic System, polycarbonate	50 x 108 x 51 mm	500 g	20% motherboard 80% polycarbonate
2 emitters	Electronic System, PVC casing	110 x 215 mm	2 x 700 g	15% motherboard 75% PVC
2 microphones on the ground	Electronic System Stainless steel Cable	123 x 45 mm	2 x 1,100 g	16.6% motherboard 75% steel 8.4% cable
1 listening rod	Electronic System Stainless steel Wiring	440 mm	1,000 g	10% motherboard 85% steel 5% wiring
1 Pair of stereo headphones	Electronic System, Conductive Cable, Foam Pads, PVC Headband and Al Coating	35 x 175 mm 1,2 m cable	118 g	5% motherboard 10% cable 80 % casing 5% foam
1 rechargeable battery	Lithium-polymer	D: 20 mm L: 70 mm	61 g	100% stack
1 transport case	Aluminum, foam, latches and metal closures	317 x 292 x 127 mm	1,360 g	95% aluminum 5% foam
Total			**6,639 g**	

Table 7-2. Technical characteristics and components of Acoustic ground microphone

EQUIPMENT CONFIGURATION: ACOUSTIC MICROPHONE TYPE				
Elements	Composition	Dimensions	Weight	Percentages
1amp unit	Electronic System, PVC casing	100 x40 x170 mm	187 g	27% motherboard 73 % PVC
1 accelerometer sensor	Electronic Equipment, PVC casing	37 x 84 mm	435 g	10% motherboard 90% PVC
1 connecting cable	Copper conductor, PVC casing	1.000 mm	0,48 g	100% cable
1 Pair of stereo headphones	Electronic Equipment, Conductive Cable, Foam Pads, PVC Headband and Al Coating	35 x175 mm 1,2 m cable	118 g	5% motherboard 10% cable 80 % casing 5% foam
4 standard 1.5V AA Alkaline batteries	Zinc and manganese dioxide	4 x (50 mm L x 14.2 mm)	4 x 26 g	100% batteries
1 transport case	Aluminum, foam, latches and metal closures	317 x 292 x 127 mm	1.360 g	95% aluminum 5% foam
Total			**2,205g**	

Other Technical Specifications:

- Power: 4 standard 1.5V AA Alkaline batteries
- Battery Life: Typically about 280 hours of operation
- Operating Temperature: -30oC to +70oC (-22oF to 158oF)
- IP protection: IP54 amplifier, IP68 sensors

Table 7-3. Technical characteristics and components of acoustic correlator

EQUIPMENT CONFIGURATION: AQUASCAN TM2 ACCOUSTIC CORRELATOR				
Elements	Composition	Dimensions	Weight	Percentages
1 correlator receiver with vehicle mount antenna	Electronic equipment PVC casing	200 x 110 x 30 mm	400g	25% plate 75% PVC
1 pair of headphones	Electronic Equipment, Conductive Cable, Foam Pads, PVC Headband and Al Coating	35 x175 mm 1,2 m cable	118g	5% motherboard 10% cable 80 % casing 5% foam
1 pair of hydrophones and connection cables	Electronic equipment Stainless steel Cables	2 x 60 mm x 68 mm	2 x 600 g	16.6% motherboard 75% steel 8.4% cable
2 transmitter sensors with antenna, cable and stand	Piezo ceramic stainless-steel electronic system Magnet (NdFeB) Cable	2 x 61 x 128 mm	2 x 1,500 g	10% motherboard 65% steel 20% rare earths 5% cable
1 Windows tablet PC	Casing, battery, motherboard, LCD screen, touchscreen frame, touchscreen	278 x 178 x 23 mm	1,000 g	100 % tablet PC
1 x 12V vehicle charger cable with 3 connectors for receiver and sensors	Electronic equipment, PVC wrapping, copper and plastic cable	1.000 mm	50 g	100% cable
1 input adapter 110-240 V AC	Electronic equipment, PVC wrapping, copper and plastic cable	120 x 59 x 35 mm 1.000 mm cable	86 g	100% adapter
2 pcs for 3.7V interchangeable 0.45A	Lithium polymer Aluminium shell	2 x 30 x 40 x 4 mm	2 x 2 g	100% batteries
1 transport case	Aluminum, foam, latches and metal closures	400 x 290 x 127 mm	1,500 g	95% aluminum 5% foam
Total			**7,358 g**	

The following considerations should be taken into account:

- The components of the three instruments are very similar to each other; they are essentially composed of receiver, emitters, transmitter sensors, battery and others passive components.

- In the transmitter sensors of the acoustic correlator equipment, it was assumed 10% to be electronic components, 20% was considered to be magnet (NdFeB), and the rest it was casing.
- The batteries interchangeable were considered to be Lithium Polymer.

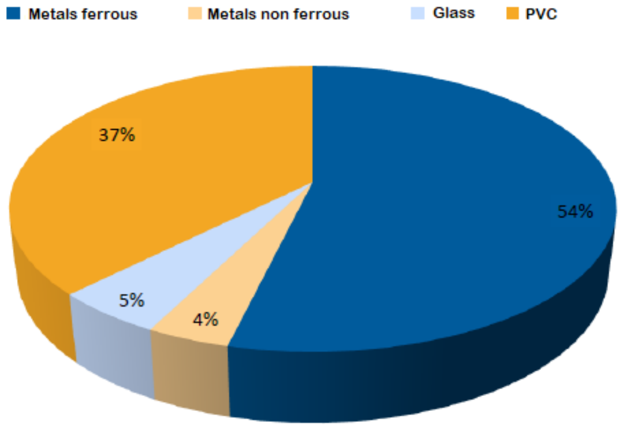


Figure 7-5. Equipment's components

Regarding the databases utilised to perform the inventory, most of the elements were selected from Ecoinvent 3.5 database and some others from the European Life Cycle Database (ELCD).

All the components of the terrestrial acoustic equipment have been identified. However, it was considering the impact of manufacturing one unit without taken into account the lifetime of each component and the amount of times that they must be replaced along the use stage.

7.2.2 Acoustic equipment operation LCI

Within the operation phase, the total power consumption of the devices constituting the functional unit has been taken into account. The most important consumption of these equipment during the use phase is due to the **rechargeable battery**.

The main impacts of the use phase are due to the electricity consumed by the equipment during its lifetime.

The lifetime of the product, multiplied by its annual energy, determines the total consumption of energy consumed in the use phase.

Some sources to consult data related to the lifetime of these components (rechargeable batteries) may be the technical specifications of this type of batteries, as well as other scientific references or documents containing information on the life cycle of such products (for example, *PEFCR - Product Environmental Footprint Category Rules for High Specific Energy Rechargeable Batteries for Mobile Applications*) covering descriptive data and a quantitative life cycle inventory.

The purpose of rechargeable batteries is to store and supply autonomous energy to electrical equipment. The scientific unit of measurement for electrical energy is the watt-hour (Wh). For rechargeable batteries, the total service provided can be measured by the total watt-hours delivered over the useful life of the rechargeable battery, measured in **kilo-watt-hours (kWh).**

The energy consumption during the use stage of the battery is defined by the energy losses linked to the efficiency of the battery and the charger during charging, unloading and storage.

Table 7-4. Lifetime of the most relevant components of the Acoustic Equipment

Component	Lifetime [years]	Equivalent units in 5 years
Acoustic equipment (general structure)	**5**	**Reference unit**
Rechargeable Batteries	2	23

Besides the replacement period of each component, the electric consumption of recharging the batteries must be included in the LCA of the operation stage.

- There are two batteries interchangeable Lithium Polymer, 3.7 V, 0.45 A /battery (Total 7,4 V).
- Battery autonomy is 20 hours.
- The batteries capacity is 450 mAh. Consequently, the electric consumption of two batteries is 0.00166 kWh, or 0.013 kW/day.

Considering all the above, the electricity consumption of the batteries in 5 years can be found in the next table.

Table 7-5. Total electricity consumption of the acoustic equipment during its lifetime

	Daily consumption	Total consumption (5 years) *
Electricity consumption	**0.66 Wh**	**0,25 kWh**

*Once a week x 15 weeks x 5 years

7.3 LCA of Acoustic Correlator

Of the three terrestrial acoustic measuring instruments analysed, the LCA of the **acoustic correlator** is performed, as it is considered the most complete and representative instrument whose components can be extrapolated to the listening bar and the ground microphone.

7.3.1 Acoustic correlator manufacturing LCA

This process takes into account the manufacture of the following adaptor, batteries, wire charger, receptor, hydrophone, sensor, tablet, headphones and briefcase. These elements have been selected as necessary to cover the computational capabilities required by a regular user. The environmental emissions and loads of the manufacturing processes of each of these elements have been determined from the inventory of materials that make up each device and the databases of the Simapro program, which are specific to the specific subject of the study.

The previous impact assessment phase provides information to assess the environmental significance of the life cycle of the selected product.

At this stage of the LCA, the data collected in the inventory are assigned to the different categories of impact analysed, according to the derived environmental effect. In the classification and characterisation, each category and flow indicator are measured on the basis of an internationally accepted reference unit. Once the Resource Use and Emissions Profile has been compiled, the impact assessment is carried out to calculate the environmental performance of the product, using the selected impact categories and models.

The purpose of the evaluation phase is to interpret the inventory, analysing and evaluating the impacts produced by the environmental loads identified in the Life Cycle Inventory. As mentioned in paragraph 3.3. of this document, 18 impact categories of the Recipe methodology have been evaluated:

Table 7-6. Impact categories included within the ReCiPe method and their units

Environmental impact category	Units
Climate change	kg CO_2 eq
Ozone depletion potential	kg CFC-11 eq
Terrestrial acidification	kg SO_2 eq
Freshwater eutrophication	kg P eq
Marine eutrophication	kg N eq
Human toxicity	kg 1,4-DB eq
Photochemical oxidant formation	kg NMVOC
Particulate matter formation	kg PM10 eq
Terrestrial ecotoxicity	kg 1,4-DB eq
Freshwater ecotoxicity	kg 1,4-DB eq
Marine ecotoxicity	kg 1,4-DB eq
Ionising radiation	kBq U_{235} eq
Agricultural land occupation	m^2a
Urban land occupation	m^2a
Natural land transformation	m^2
Water depletion	m^3
Metal depletion	kg Fe eq
Fossil depletion	kg oil eq

In the database used, the allocation of material/energy inputs and outputs inventoried in the Resource Use and Emissions Profile to the relevant impact category has already been carried out.

Of the different stages of the life cycle (Raw material acquisition, Product Production, Distribution, Use Stage and End-of-Life), the **assembly process** is the most significant.

The next table contains the LCA impact results, in absolute values, for all the impact categories analysed by the calculation method (ReCiPe Midpoint (H)). The categories selected to be analysed in more detail are marked in bold: climate change, ozone depletion, terrestrial acidification, freshwater eutrophication and human toxicity.

Table 7-7. Environmental Impact of Acoustic Correlator manufacture

Impact category	Unit	Total	Adaptor	Battery	Brief case	Wire charge	hydrophone	Receptor	Sensor	tablet	Headphones
Climate change	**kg CO$_2$ eq**	**263,42**	**0,45**	**0,03**	**8,65**	**5,62**	**45,38**	**22,02**	**121,57**	**54,98**	**4,72**
Ozone depletion	**kg CFC-11 eq**	**1,52E-04**	**5,79E-07**	**1,99E-08**	**4,49E-06**	**9,07E-06**	**2,62E-05**	**1,25E-05**	**7,04E-05**	**2,56E-05**	**3,13E-06**
Terrestrial acidification	**kg SO$_2$ eq**	**1,45**	**0,01**	**3,53E-04**	**0,04**	**0,17**	**0,24**	**0,11**	**0,60**	**0,24**	**0,03**
Freshwater eutrophication	**kg P eq**	**0,84**	**2,40E-03**	**7,49E-05**	**3,04E-03**	**0,04**	**0,17**	**0,08**	**0,39**	**0,12**	**0,02**
Marine eutrophication	kg N eq	3,08E-02	1,45E-04	5,04E-06	5,06E-04	2,55E-03	4,47E-03	2,06E-03	1,08E-02	9,67E-03	5,71E-04
Human toxicity	**kg 1,4-DB eq**	**36,35**	**0,70**	**4,74E-03**	**1,02**	**1,87**	**6,98**	**3,27**	**15,89**	**5,88**	**0,74**
Ozone formation human	kg NOx eq	0,76	2,06E-03	8,45E-05	0,02	0,03	0,14	0,07	0,34	0,14	0,01
Ozone formation Terrest.	kg NOx eq	0,79	2,11E-03	8,68E-05	0,02	0,03	0,15	0,07	0,35	0,15	0,01
Particulate matter formation	kg PM2.5 eq	0,69	3,69E-03	1,32E-04	0,02	0,06	0,12	0,05	0,29	0,14	0,01
Terrestrial ecotoxicity	kg 1,4-DB eq	3690,44	59,47	1,72	32,75	1053,62	540,08	198,67	1273,26	418,13	112,74
Freshwater ecotoxicity	kg 1,4-DB eq	137,95	0,44	0,01	0,34	7,61	28,56	13,76	64,79	19,40	3,03
Marine ecotoxicity	kg 1,4-DB eq	195,33	0,64	0,02	0,48	11,03	40,54	19,52	91,59	27,22	4,30
Ionising radiation	kBq U235 eq	23,93	0,07	0,01	1,94	1,12	4,04	1,94	10,60	3,72	0,50
Land use	m^{2}a crop eq	5,19	0,02	7,96E-04	0,50	0,39	0,93	0,43	1,97	0,85	0,10
Water consumption	m^3	2,29	0,01	3,33E-04	0,11	0,08	0,36	0,22	1,07	0,39	0,05
Mineral depletion	kg Cu eq	8,26	0,04	1,40E-03	0,12	0,60	2,04	0,95	3,29	1,05	0,17
Fossil depletion	kg oil eq	70,24	0,12	0,01	2,03	2,08	10,91	5,52	33,12	15,25	1,19

In order to further analyse where these impacts come from, next figure depicts the relative contributions of the elements which are part of the acoustic correlator unit. In this case, results show that the main contribution, comes from the "sensor" due to its components (electronic system and magnet). Note the condition of the "wire charger" on "Terrestrial Ecotoxicity" impact.

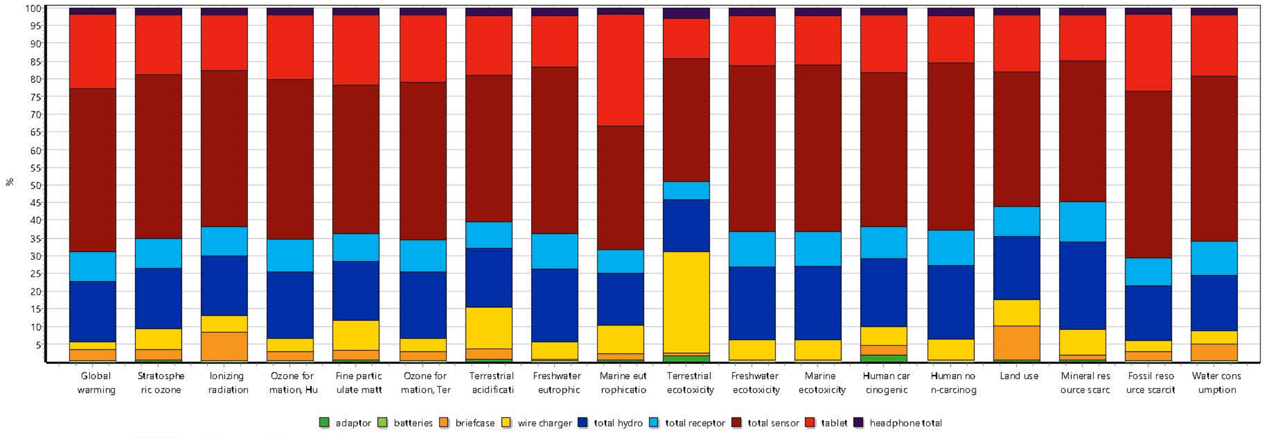


Figure 7-6. LCA environment impact categories Assembly Stage

The figure shows the relative environmental impact of the eighteen selected impact indicators divided by all equipment components. The electronic components and the sensor magnet have the main impact for all categories. Its influence is particularly significant on some indicators, such as climate change or ozone depletion, whose contribution is more than 40% of the total environmental burden associated with complete acoustic equipment. In general, all elements with electronic components cause more impact than passive components (plastics, foam, etc.).

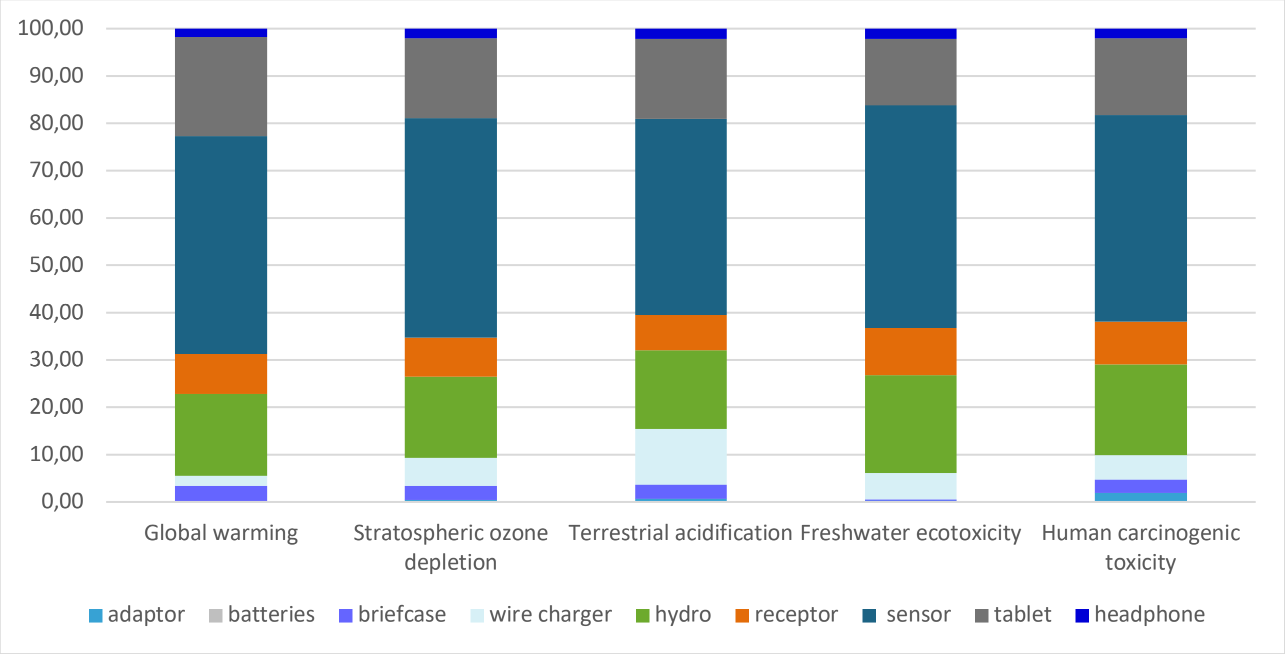


Figure 7-7. More significant LCA environment impact categories

7.3.2 Acoustic correlator operation LCA

In the LCI, a service life of the acoustic equipment has been considered as a functional unit of 5 years. The electricity consumed to recharge the batteries during the use phase of the equipment is analysed below.

Equipment	Components	Useful life
Acoustic Correlator	Functional unity	5 years

As in the previous case of the LCA of drones and aircraft, depending on the country where the electricity is generated, the environmental impacts associated with its generation can vary considerably. In this case, SGI Studi Galli Ingegneria, as an Italian partner of the WADI project, provided the technical characteristics of the acoustic appliances and it was decided to take as reference the electricity generated in Italy. Besides, the average low voltage electricity mix of EU-28 has been considered to check the representativeness of the mentioned countries in the European electricity production.

The results obtained in the LCA can be found in the next table. On one hand, the green columns contain the impact caused by components assembly taken into account its lifetime and the periodicity with which they must be replaced. On the other hand, the orange columns contain the impact caused by the electricity consumption if the Italian electricity or mixed is considered.

Table 7-8. Absolute environmental impact of the acoustic correlator and its electricity consumption (operation stage)

Impact Category	**Units**	**Acoustic Correlator**	**Electricity Italy**	**Electricity Mixed**
Climate change	**kg CO_2 eq**	**263,42**	**0,01**	**1,86**
Ozone depletion	**kg CFC-11 eq**	**1,52E-04**	**9,13E-09**	**1,14E-07**
Terrestrial acidification	**kg SO_2 eq**	**1,45**	**7,33E-05**	**1,78E-04**
Freshwater eutrophication	**kg P eq**	**0,84**	**3,05E-06**	**3,66E-05**
Marine eutrophication	kg N eq	0,03	2,30E-07	1,29E-03
Human toxicity	**kg 1,4-DB eq**	**36,35**	**1,77E-04**	**0,04**
Particulate matter formation	kg PM2,5 eq	0,69	1,91E-05	8,40E-05
Terrestrial ecotoxicity	kg 1,4-DB eq	3690,44	0,01	0,02
Freshwater ecotoxicity	kg 1,4-DB eq	137,95	8,91E-05	1,07
Marine ecotoxicity	kg 1,4-DB eq	195,33	1,27E-04	1,41
Ionising radiation	kBq U235 eq	23,93	2,10E-03	2,18E-03
Urban land occupation	m^{2}a crop eq	5,19	3,58E-04	8,49E-04
Water depletion	m^3	2,29	2,39E-04	1,22E-04
Mineral depletion	kg Cu eq	8,26	2,01E-06	3,54E-06
Fossil depletion	kg oil eq	70,24	3,43E-03	5,91E-03

The electricity consumed to recharge the batteries of acoustic equipment during the use stage only represents 0.001% of the weight on the studied environmental impacts.

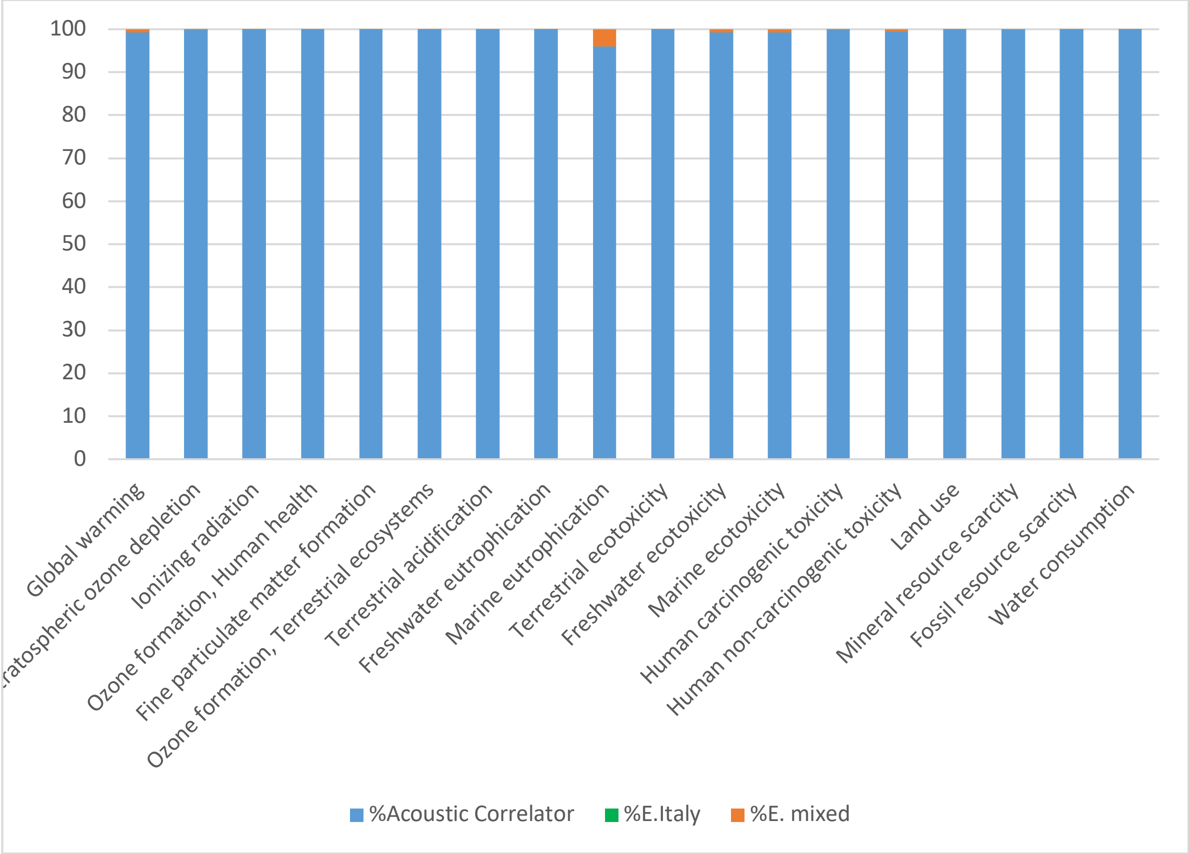


Figure 7-8. LCA Operation Stage

As can be seen the value of the indicators is similar in both cases being not significant the origin of electricity in this LCA. The greatest impacts of energy consumption are concentrated in Global warming and Human toxicity.

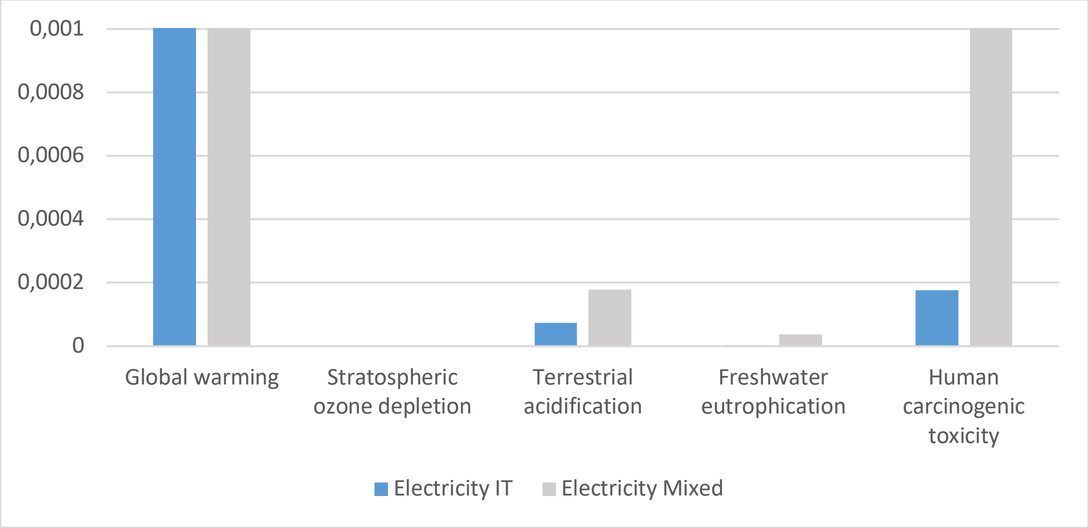


Figure 7-9. Relative impact of the Acoustic Correlator if the electricity of Italy or Mixed is considered

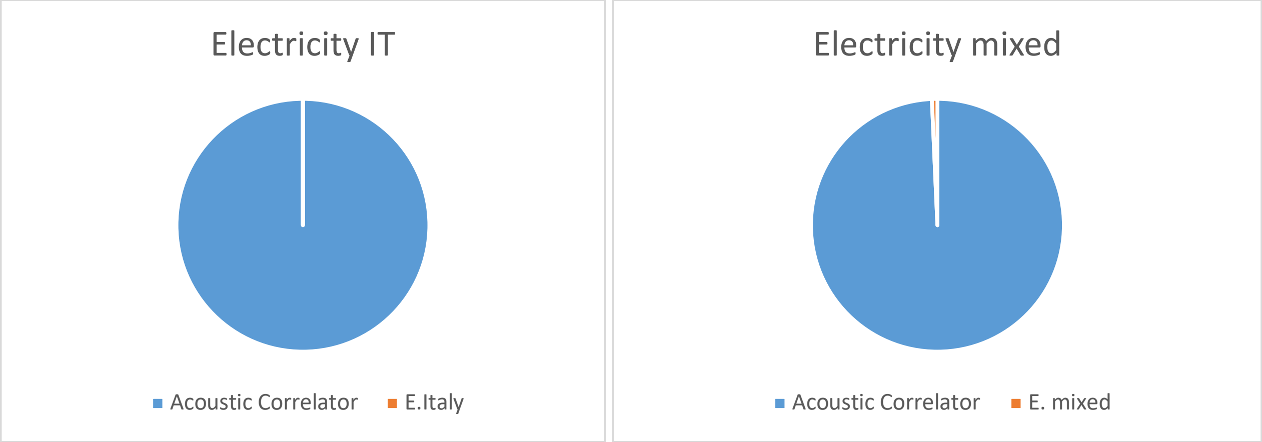


Figure 7-10. Contribution of the acoustic correlator electricity consumption to the total environmental impact of the equipment

In summary, electricity consumption has a negligible environmental impact on all indicators. Moreover, there are hardly any differences between electricity generated in Italy or from mixed sources.

Finally, it can be concluded that although the batteries have the greatest impact on the production of the acoustic correlator, the energy consumption to recharge them during the use phase is not significant.

7.4 LCA results and discussion

Today the main method of detecting water leakage works with acoustic signals; acoustic sensors are placed on underground mains water pipes where water leakage causes mechanical vibrations that are displayed on a monitoring screen in a way these sensors detect the sound of water leaking out of a pipeline, but the acoustic detection techniques are accurate only for small diameters pipe.

The WADI project is working on new technologies to make remote locations more accessible.

The technology being developed within the watering project allows water losses in places which are difficult to access such as rural areas as well as the opportunity to study and investigate losses in large-diameter transmission pipes where the normal and traditional technologies are not very efficient in terms of cost and accessibility.

With WADI technology, using small planes and drones, equipped with multispectral and infrared cameras, they are able to spot water leakages in large rural, inaccessible and dangerous places, where current ground methods, like the acoustic survey, fail.

The LCA methology aims to compare the impacts generated during the different stages of the Life Cycle between the two study techniques (WADI technology/Acoustic correlator).

LCA is a tool aimed at understanding the environmental performance of a given service, product or organization, as well as to establish the potential impacts associated with its production and use through the quantification of the environmental loads generated in its life cycle.

In this case, the impact of the manufacture and the Use stage of the manned aircraft is completely outside the permissible range of comparison for UAV/Correlator. Shall therefore only be taken into account the LCA of the drone and the correlator.

Table 7-9. LCA results of WADI technologies and Acoustic Correlator

Impact category	Unit	Total MAV	Total UAV	Total Correlator
Climate change	**kg CO_2 eq**	2,31E+04	261,75	263,42
Ozone depletion	**kg CFC-11 eq**	1,79E-03	3,76E-05	1,52E-04
Terrestrial acidification	**kg SO_2 eq**	109,84	261,75	1,45
Freshwater eutrophication	**kg P eq**	14,37	0,94	137,95
Human toxicity	**kg 1,4-DB eq**	2,50E+04	584,45	36,35

However, it should be noted that these studies should not be taken as a direct comparative framework, since the components considered for the environmental analysis of each equipment may be different from those considered in this LCA according to the model and brand available on the market. In other words, it must be taken into account that the results obtained can vary significantly depending on the source data considered for the calculation of the indicators in each case.

The impact on Climate change indicator is similar in both cases (261,75/263,42 kg CO_2 eq). However, the production of the UAV has a much greater impact on the indicators of Terrestrial acidification and Human toxicity.

The electricity consumption in the case of the acoustic correlator represents only 1% in the majority of indicators in the use phase. While in the case of the UAV it represents 80% on the water resource (Water depletion).

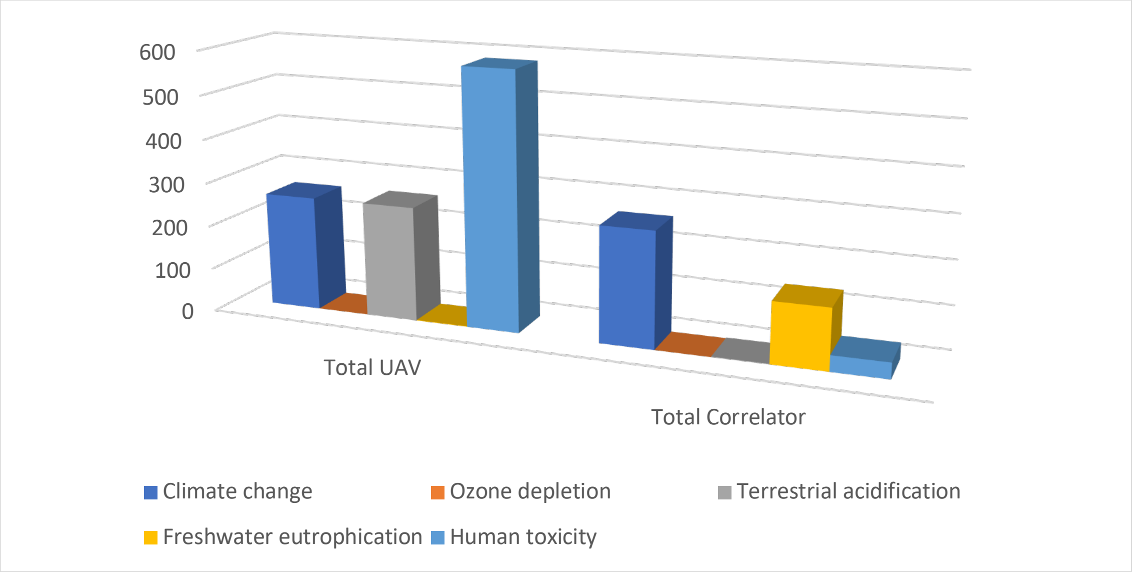


Figure 7-11. Impact manufacturing UAV / Acoustic correlator

7.4.1 Advantages and disadvantages

Acoustic technologies for leakage control

- ✓ Acoustic equipment is the most traditionally used instrument for leak detection.
- ✓ The most advanced instruments are the automatic acoustic correlator equipped with sensors, receivers and remote computer, all relatively simple technology.
- ✓ They enable the exact location of the leak to be determined by avoiding thorough field search operations.
- ✓ They generally run on a pair of rechargeable batteries with an average range of 20 hours.
- ✓ The electricity consumption to recharge the batteries is noticeably lower than the energy needed to power the drones (UAV) for example.
- Acoustic equipment is only required for small pipe diameters.
- They cannot be used in places of low accessibility.
- The noise recorders have a powerful magnet installed at the base to be attached to any metal device. The impact associated with the manufacture of the magnet is quite significant on the overall assembly of the equipment.

WADI technologies (MAV-UAV)

- ✓ Planes and drones of WADI technology are equipped with multispectral and infrared cameras on state of the art.
- ✓ Detect water leaks precisely thanks to the synergetic use of TIR and multispectral images combined with the data processing for soil moisture evaluation.
- ✓ Measure soil humidity through optimised wavelengths detection (multispectral for visible, near infrared and long infrared domain for TIR).
- ✓ Can implement WADI's service on a wide range of water suppy systems including infrastructures such as dams, reservoirs, pressurised and gravity mains, canals, etc.
- ✓ The general objective of wadi is to contribute to the reduction of losses in water transmission systems for water supply, irrigation and hydroelectricity and, at the same time, **to reduce related energy consumption.**

For all these reasons, it seems clear that although the carbon footprint of traditional acoustic equipment is significantly lower than the WADI technologies, the extent of the expected results in leak detection is much more efficient with the use of manned aircraft and drones.

8 Conclusions

The present deliverable contains a LCA of both WADI units developed along the project: MAV a UAV. In order to obtain all the information required to perform these studies, data gathering template were sent to the responsible partners. Those templates requested information related to the characteristics of the components involved in the WADI detection units (cameras, aircrafts…), the manufacturing stages of the WADI units, and also, information related to the flights and the working conditions.

The main conclusions obtained for each kind of WADI water leaks detection technique are:

Manned Aircraft Vehicle (MAV)

- The carbon footprint of manufacturing one unit of MAV is 23,100 kg CO_2-eq and the water footprint is 157,717 m^3/unit.
- The greatest contributor to most of the environmental categories is the impact of the plane. For example, its contribution is over 99 % in some indicators such as climate change, ozone depletion and water depletion. Concretely, the impact associated with the aluminium use and the electricity used during the manufacturing phase of the plane are the most relevant impacts. The impact of the IR camera in the human toxicity indicator is very high (about 92 %) due to the presence of mercury in the IR detector. The impact of the other components is lower and mainly due to the electronic components.
- When all the consumptions incurred during the use stage of the MAV, as well as the lifetime of each component, are analysed, it is observed that the fuel consumption is the greatest contributor in most of the environmental indicators (e.g., climate change 91 %, ozone depletion 98 %, and fossil fuel depletion 99 %). The impacts associated with the MAV manufacturing are small in comparison, except the impact of the IR camera in the human toxicity indicator, which is still significant (76 %).

Unmanned Aircraft Vehicle (UAV)

- Regarding the manufacturing of one unit of UAV, the drone has the greatest contribution in all the environmental indicators considered in this study (more than 90 %), especially because of the electronic components and the battery cells impacts. Furthermore, for the UAV, the IR camera does not have hardly impact in the human toxicity indicator since there is not mercury on its IR detector.
- When the use stage is analysed, the electricity consumption required to charge the batteries originates most of the environmental impact on many indicators. When this happens, it is very important to stablish the electricity mix that will be used because this can strongly change the results. In this case, the French and Portuguese electricity mixes were evaluated. In France, the ionizing radiation indicator is very high because of the big weight of nuclear energy. On the other hand, the electricity mix of Portugal has a big proportion of fossil fuel sources, and consequently, some indicators such as climate change and fossil fuel depletion are much greater than in France.
- Besides the big impact of the electricity consumption during the use stage, the drone battery impact is significant in most of the indicators. This result is a consequence of taking into account the lifetime and the replacement period of the components,

since the lifespan of the batteries is lower than the lifespan of other components of the UAV.

9 References

[1] "UNE-EN ISO 14040:2006 - Environmental management- Life Cycle Assessment- principles and framework." International Organization for Standardization, 2006.

[2] "UNE-EN ISO 14041:1998 - Environmental Management – Life cycle assessment. Goal and scope definition and Inventory analysis. ." International Organisation for Standarisation, 1998.

[3] J. Vasco de Oliveira, "Life Cycle Assessment of the Airbus A330-200 Aircraft," *Assessment*, p. 140, 2010.

[4] M. Chester, "Life-cycle environmental inventory of passenger transportation in the United States," University of California, 2008.

[5] J. Verstraete, "Creating a Life-Cycle Assessment of an Aircraft," Hamburg University of Applied Sciences, 2012.

[6] J. Sousa Ribeiro and J. De Oliveira Gomes, "Proposed framework for end-of-life aircraft recycling," Elsevier B.V., 2015.

[7] J. C. Bare, P. Hofstetter, D. W. Pennington, and H. A. U. de Haes, "Midpoints versus endpoints: The sacrifices and benefits," *Int. J. Life Cycle Assess.*, vol. 5, no. 6, p. 319, Nov. 2000.

[8] various authors PRé, "SimaPro Database Manual Methods Library," 2018.

[9] "Ecoinvent." [Online]. Available: www.ecoinvent.org.

[10] "LCI databases in SimaPro." [Online]. Available: https://simapro.com/databases/.

[11] "TECNAM. Quality aircraft since 1948." [Online]. Available: https://www.tecnam.com/. [Accessed: 20-Jun-2018].

[12] "SpectroCam Multispectral Cameras." Pixelteq, 2016.

[13] "NOXANT Amazing Optronics by Passionate People." [Online]. Available: https://www.noxant.com/index.php/fr/produits/noxcam-hsi. [Accessed: 23-Jul-2018].

[14] "Spatial Dual datasheet." Advanced navigation, 2017.

[15] P. Norton, "HgCdTe Infrared Detectors," *Opto-Electronics Rev.*, vol. 10, no. 3, pp. 159–174, 2002.

[16] I. Trudeau, "Chapter- 4 Mercury Telluride and Mercury Cadmium Telluride," in *Chemistry and Applications of Mercury*, Open Court Publishing Company, 2012.

[17] "Carbon Fiber Education Center. Zoltek website." [Online]. Available: http://zoltek.com/carbon-fiber/how-is-carbon-fiber-made/. [Accessed: 31-Jul-2018].

[18] B. Neuberger, "An Exploration of Commercial Unmanned Aerial Vehicles (UAVs) Through Life Cycle Assessments," Rochester Institute of Technology, 2017.

[19] "FLIR Vue Pro R Datasheet." FLIR.

[20] "Uncooled detectors for thermal imaging cameras." FLIR, Breda - Netherlands, p. 6, 2008.

[21] "Cobalt in Hard Metals and Cobalt Sulfate, Gallium Arsenide, Indium Phosphide and Vanadium Pentoxide," in *IARC Monographs on the Evaluation of Carcinogenic Risks to Humans*, Lyon (France): International Agency for Research on Cancer, 2006.

[22] AIRBUS, "Process for Advanced Management of End-of-Life of Aircraft," 2008.

[23] E. P. and C. D. 2008/98/EC, “Directive 2008/98/EC of the European Parliament and of the Council of 19 November 2008 on waste and repealing certain Directives,” 2008.

[24] P. S. Towle, I; Johnston, C; Ligwood, R; Grant, “The aircraft at the End of Life Sector: A Preliminary Study,” 2004.

[25] S. Pimenta and S. T. Pinho, “Recycling carbon fibre reinforced polymers for structural applications: Technology review and market outlook,” *Waste Manag.*, vol. 31, no. 2, pp. 378–392, 2011.

[26] J. Palmer, O. R. Ghita, L. Savage, and K. E. Evans, “Successful closed-loop recycling of thermoset composites,” *Compos. Part A Appl. Sci. Manuf.*, vol. 40, no. 4, pp. 490–498, 2009.

[27] M. J. Smith and F. M. Gray, “Batteries, from Cradle to Grave,” *J. Chem. Educ.*, vol. 87, no. 2, pp. 162–167, 2010.

[28] F. Saloojee and J. Lloyd, “Lithium Battery Recycling Process,” vol. 27, no. 0, p. 35, 2015.

10 ANNEX A

10.1 Manned and unmanned aircrafts disposal strategies

Airbus endorsed a commitment towards a responsible environmental management throughout the life cycle of the aircraft, namely, its final stage.

With the PAMELA project, a valorisation of 68 % of the total aircraft weight is obtained, even though new research is being developed by Airbus in order to improve this scenario, being that the major challenge resides in recycling composites and recycling parts in which materials are difficulty separated correctly.

Traditionally, aircraft have been stored in deserts, abandonment in airports, wild destruction of non-ferrous salvaged materials, or other locations considered as "aircraft graveyards". However, the significant development in the aviation sector caused a growing concern about the aircrafts end-of-life by all the participants in the aviation industry and society. Besides, the worldwide demand for raw and secondary materials continues to increase and landfilling does not seem to be a suitable long-term solution of handling aircraft at their end-of life stage any more.

Under this situation, two of the most important companies of the aviation sector such as Airbus and Boing have developed different researching studies in order to better manage the aircrafts after their use stage since this has not been legally regulated yet. The name of the most important project carried out by Airbus in this matter is called PAMELA project (Process for Advanced Management of End-of-Life Aircraft), while Boeing founded the industry association AFRA (Aircraft Fleet Recycling Association) along with other aviation companies. In these studies, both companies show different possibilities and limitations of the aircraft end-of-life processes considering the alternatives of re-use, recycling and landfilling.

Each kind of aircraft should apply a specific end-of-life strategy in order to maximize the positive effects from an economic, environmental and social criterion. However, there is a lack of studies in the literature supporting the decision-making process about which end-of-life alternative is the most suitable for each case. Even though in the last year huge advances were done to improve the management of the aircrafts after their use stage, there is still a long way to go.

10.2 PAMELA project (Airbus)

As mentioned before, the effort of Airbus to create a general framework to improve the end-of-life strategies in the aircraft management. PAMELA project (Process for Advanced Management of End-of-Life Aircraft) started in 2005 and was funded under the European Programme Life+. The consortium of this project was leaded by Airbus and was completed in 2007, after 32 months. The objectives of the PAMELA project can be summarized in the following three points [22]:

- To demonstrate, by full-scale experimentation on aircraft, that 85 % of the weight of an aircraft can be recycled, reused or recovered.
- To set up a new appropriate standard for safe and environmentally responsible management of the End-of-Life of Aircraft. This process will cover all aspects, from

storage (D1) to disassembling (D2), smart and selective dismantling (D3) and recycling or elimination of materials or parts through controlled dedicated processes.

- To install, through an efficient, competent and complementary partnership, international network capable of further disseminating the so-called 3D process (D1, D2, D3).

A general overall of the proposed 3D approach can be found in Figure 10-1.

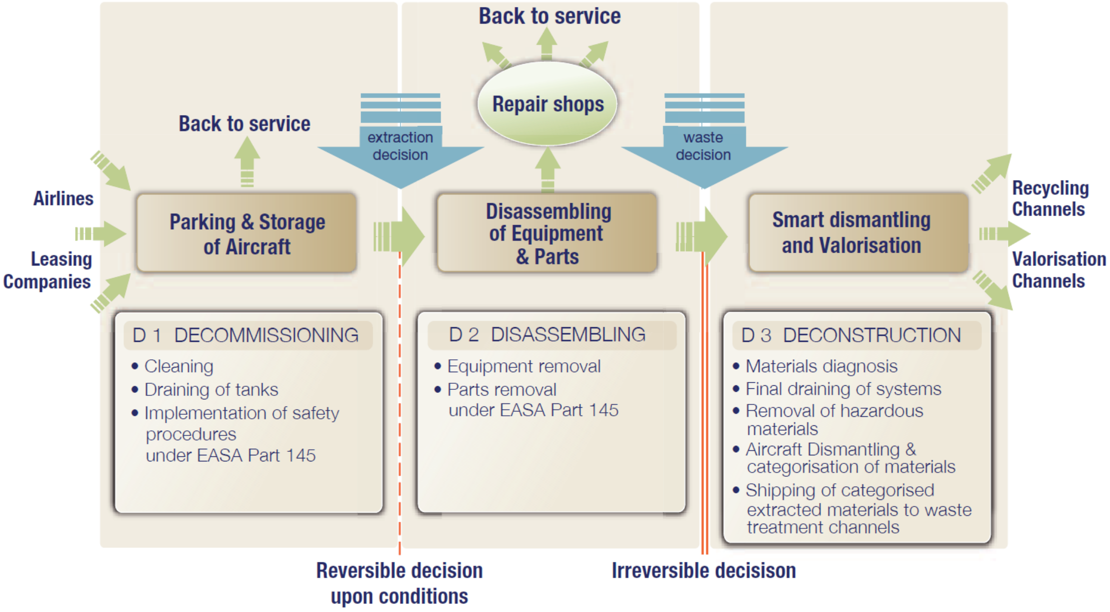


Figure 10-1. PAMELA's 3D approach of handling end-of-life aircraft [22]

10.2.1 D1 - Decommissioning

This is the first stage carried out after ending the use stage of the aircraft. Its first step consists of inspecting the aircraft in order to create a list of the parts that could be later dissembled and reused. Then, the aircraft is cleaned and decontaminated. Besides, all the tanks and piping are drained. On the one hand, some of those fluids can be directly sold or re-used and generate benefit (e.g. fuel or oil). On the other hand, fluids that cannot be reused are disposed by the specific recovery channels defined in the existing regulation.

10.2.2 D2 – Disassembly

Disassembly can be defined as process of taking apart the different constituent parts of a system, or what is the same, carrying out the physical separation of the components. Some of these disassembled components are engines, avionics, and landing gears, among others. To do this stage, a disassembly sequence planning is firstly proposed. Its aim is to stablish the order in which the components will be removed as well as sort them into disassembly families.

10.2.3 D3 – Smart and selective dismantling

In this stage, different strategies to recovery materials were identified. Firstly, the aircraft must be dismantled and for this purpose, some technologies were proposed as the most adequate tools to separate the recoverable materials: plasma torch, high-pressure water jet, angle grinder with different types of abrasive discs, chainsaw and hydraulic scissors. Later, all these materials are sorted, grouped and shredding, before going to the different recovery channels (aluminium alloys, non-ferrous metals, stainless steel, wiring, tires, and plastics). For example, some metals are melted and cast in order to generate new metal ingots that can be used in different industrial sectors (aeronautic, mechanical or automobile) as raw material according to their chemical composition.

10.3 End-of-life aircraft recycling

Recycling can be defined as any recovery operation by which waste materials are reprocessed into products, materials or substances whether for the original or other purposes. It includes the reprocessing of organic material but does not include energy recovery and the reprocessing into materials that are to be used as fuels or for backfilling operations [23]. In [6], Sousa and Oliveira enumerate four motivations for recycling the different components of aircrafts:

1. At the end of the useful stage, the aircraft still has a rest value that should be recovered.
2. The production of new aircrafts requires raw materials, capital, energy and labour. Trough recycling or reuse, a great amount of materials or components can be recovered and this way, primary and natural resources can be saved.
3. The production of secondary raw materials required significantly less energy than the production of primary raw materials. Therefore, recycling leads to a reduction of emissions to air, water and soil.
4. Recycling leads to a reduction of waste, and consequently, a reduction of land use in landfill sites.

In the following sections, the most common recycling treatments for the main components of the aircraft are described.

10.3.1 Composites recycling

The amount of these components in the aircraft structure is one of the most important. In fact, some of the market leaders such as Boing or Airbus announced to use up to 50 % of polymeric based composites in their primary structures. The increased use of composites allows obtaining a reduction in the aircraft weight, reduction in the number of components and reduction in the maintenance costs. Some of the most habitual composites are glass fibre and aluminium (GLARE) composite or carbon fibre reinforced plastic (CFRP) composite [24].

For many years, many composites were considered to be non-recyclable because disposal by landfill was an easy and cheap option. However, now there are other alternatives to recover these materials, for example a nitric acid treatment to dissolve the thermoset resin, incineration process or thermal pyrolysis, among others. Special attention requires the latter alternative since that could be considered the best alternative for large scale aircrafts. After being incinerated, recovered carbon fibres could potentially be used in other aerospace applications. If not, they can be used in other sectors such as automotive, construction or marine.

10.3.2 Cabin Interiors

The disposal strategy of the cabin interiors is a concern for both the airframe disposal companies and operating airlines. The cabin contains many different materials that must be removed by hand if they want to be properly recovered. The major components are made of composites based on polymers or different kinds of plastics, which are intimately inter-mixed. For this reason, the most frequent option is to send those fittings to landfill.

Towle and cols [24] identify some challenges /opportunities that still must be faced to achieve a successful recovery of the cabin components.

- Efficient Separation of organic materials from metallic and composite materials.
- Identification of the different classes of material, metals and non-metals.
- Developing efficient and commercially viable re-processing technologies.
- Finding suitably high value markets for the recovered materials.

10.3.3 Metal separation technologies

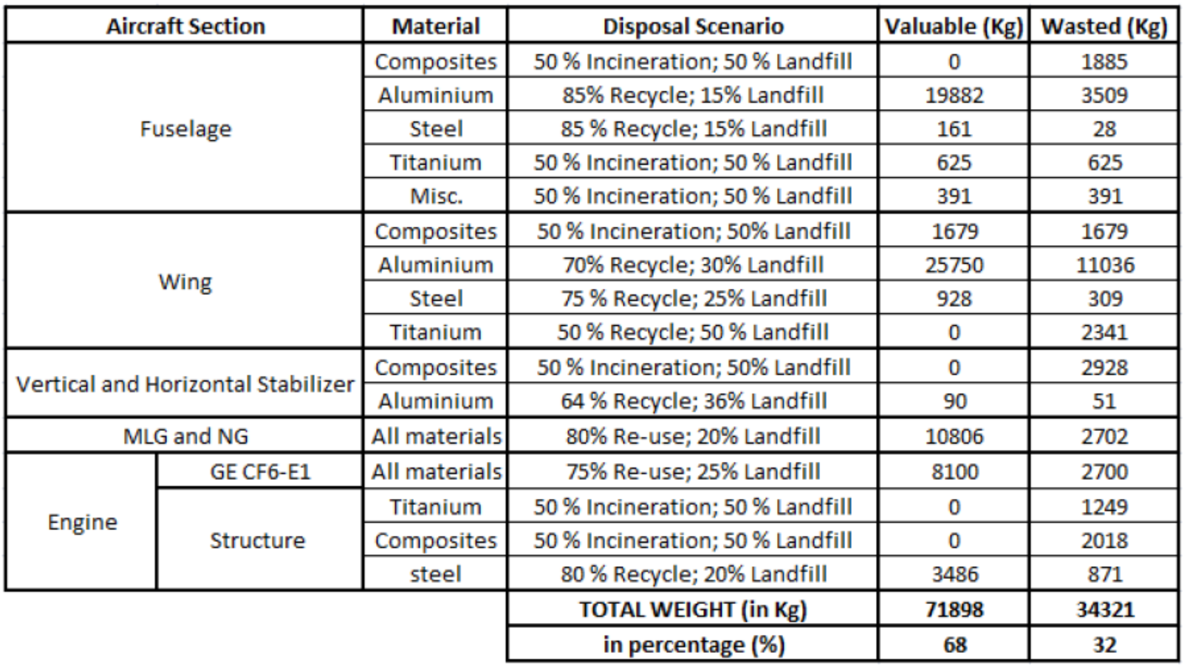
After removing high value component materials from the airframe, the remaining materials are broken up into small pieces and sent a metal smelter for processing. Since these materials are composed by a mixture of many kinds of alloys and materials, its value is low. However, it could be significant if the components could be readily separated into purer materials streams.

10.3.4 End-of-life strategies after PAMELA approach

As mentioned before, PAMELA program was developed by Airbus to set up a framework from which to stablish a reference protocol about different alternatives and strategies to manage airframe retiring for the benefit of a more eco-efficient aerospace industry.

According to [3], despite the technological availability for recycling most of the materials that compose an aircraft, it is difficult to separate all materials to the correspondent material type (metallic, composites, elastomers, etc.). For this reason, PAMELA project was able to reach a valorisation of 68 % of the total aircraft weight. The results obtained are collected in Table 10-1.

Table 10-1. End-of-life scenario for the A330-200 aircraft, according to the PAMELA Project by AIRBUS



Aircraft Section		Material	Disposal Scenario	Valuable (Kg)	Wasted (Kg)
Fuselage		Composites	50 % Incineration; 50 % Landfill	0	1885
		Aluminium	85% Recycle; 15% Landfill	19882	3509
		Steel	85 % Recycle; 15% Landfill	161	28
		Titanium	50 % Incineration; 50 % Landfill	625	625
		Misc.	50 % Incineration; 50 % Landfill	391	391
Wing		Composites	50 % Incineration; 50% Landfill	1679	1679
		Aluminium	70% Recycle; 30% Landfill	25750	11036
		Steel	75 % Recycle; 25% Landfill	928	309
		Titanium	50 % Recycle; 50 % Landfill	0	2341
Vertical and Horizontal Stabilizer		Composites	50 % Incineration; 50% Landfill	0	2928
		Aluminium	64 % Recycle; 36% Landfill	90	51
MLG and NG		All materials	80% Re-use; 20% Landfill	10806	2702
Engine	GE CF6-E1	All materials	75% Re-use; 25% Landfill	8100	2700
	Structure	Titanium	50 % Incineration; 50 % Landfill	0	1249
		Composites	50 % Incineration; 50 % Landfill	0	2018
		steel	80 % Recycle; 20% Landfill	3486	871
			TOTAL WEIGHT (in Kg)	**71898**	**34321**
			in percentage (%)	**68**	**32**

10.4 End-of-life drone strategies

Drone is formed by two main components: the drone structure, which is based on carbon fibre composites, and the LiPo batteries. The first step after finishing the use lifetime of the drone is disassembling these components. They both must be independently managed.

10.4.1 Drone structure recycling

The main component of the drone structure is carbon fibre; concretely, a carbon fibre reinforced polymer (CFRP). Presently, most of the CFRP waste is landfilled. However, the worldwide demand for carbon fibres and its growing market makes necessary to develop recovering and recycling process in order to increase the sustainability of an emerging component.

Recycling composites is difficult because of their complex composition, the cross-linked nature of thermoset resins and the combination with other materials [25]. However, it is important to overcome this unfavourable situation for the following reasons:

- Environmental impact: The increasing amount of CRRP applications cause an increase in the waste and consumption of non-renewable energies.
- Legislation: European legislation is enforcing a strict control of composites disposal with some directives such as EU 99/31/EC or EU 2000/53/EC.
- Production cost: Recovery of fibres requires much less energy than production of virgin fibres.
- Security of supply: Demand for virgin fibre expected to exceed supply very soon, so primary producers may be selective when meeting orders.

In this light, four recycling strategies are proposed in this deliverable: mechanical recycling, pyrolysis, fluidised bed and chemical recycling [25].

10.4.1.1 Mechanical recycling

This treatment involves breaking-down the composites by shredding, crushing or milling processes, obtaining scrap pieces that can be segregated by sieving into powdered products and fibrous products [26].

Composites recovered by this treatment can be re-incorporated in new composites as reinforcement or be used, for example, in the construction induction as fillers for artificial woods or asphalt. In all cases, all these uses represent low-value applications.

10.4.1.2 Pyrolysis

Pyrolysis is one of the most widespread recycling processes for CFRP. In fact, this is currently the only process with commercial-scale implementations. The pyrolysis process is based on the thermal decomposition of organic molecules in an inert process. CFRP is heated up to 450 to 700 ºC in absence of oxygen. At this temperature, the polymeric matrix is volatilized into lower weight molecules, while the CFs remain inert and are eventually recovered.

10.4.1.3 Oxidation in fluidised bed

This process is another thermal process for CFRP recycling which consists of combusting the polymeric matrix in a hot and oxygen-rich flow between 450 and 550 ºC.

In this process, CFRP scrap is fed into a bed of silica. As the hot air stream passes through the bed and decomposes the resin, both the oxidised molecules and the fibre filaments are carried up within the air stream, while heavier metallic components sink in the bed and the resin is fully-oxidised in an afterburner.

10.4.1.4 Chemical recycling

Chemical methods for CFRP recycling are based on a reactive medium, under low temperature (typically <350 ºC). The polymeric resin is decomposed into relatively large (and therefore high value) oligomers, while the CFs remain inert and are subsequently collected.

10.4.2 Batteries recycling

Regarding the end-of-life treatment for the batteries, many of them still end up in landfills or are incinerated because of inefficient national collection and recycling schemes. However, they content many chemical components that can negatively affect to the environment of even to the human health.

When disposal is the only end-of-life option, heavy metals are normally treated by stabilization and inertisation in order to avoid leaching. This way, the toxicity is reduced by making insoluble or immobilizing the hazardous waste. However, and unlike recycling, the inertised materials do not have commercial value.

The most adequate end-of-life treatment is recycling. However, the diversity of batteries chemistries has also led to a wide rand of recycling treatments. Preliminary procedures involve removal of labels, opening of cell casings, and destroying of seals and separators by procedures based on mechanical cutting, chopping or pyrolysis. The secondary stages of recycling are broadly classified as hydrometallurgical or pyrometallurgical.

On the one hand, hydrometallurgic techniques include acid, alkaline or solvent extraction. Here, metal solutions are generated and then subjected to precipitation, selective reactions or electrolysis to isolate the purified materials. On the other hand, pyrometallurgic procedures use high temperatures to separate metals and be subsequently recycled. A general scheme of different batteries recycling strategies can be found in Figure 10-2.

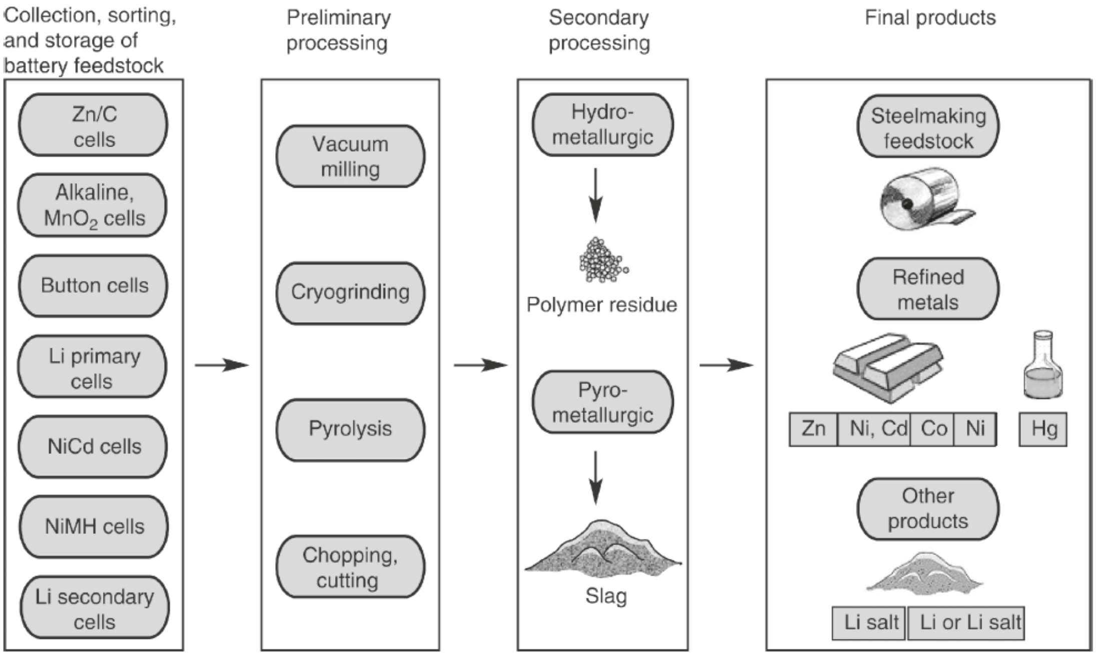


Figure 10-2. General recycling procedure for all types of batteries [27].

Concretely, for the lithium batteries as those used in the drone of the WADI project, one of the most frequent treatments was developed by the company *Toxco*. In this procedure, lithium is recovered as the metal or lithium hydroxide. Initial processing of batteries feedstock involves cryogrinding and reacting with water to produce hydrogen, which can be burnt off above the reaction liquid. Other methods were developed by *Recupyl*, where physical and chemical treatments are combined to produce lithium carbonate, or by *Umicore*, whose process is based in pyrometallurgical techniques [28].