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Cradle-to-grave Life Cycle Assessment of European Space Agency's New Norcia space-tracking terminal

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ABSTRACT

The transition to a low-carbon and resource-efficient circular economy is a political pillar of the European Union and a priority for space agencies. Indeed, the space industry is pursuing sustainable development practices to reduce the environmental impacts related to the various activities they perform, just like any other industry. Life Cycle Assessment (LCA) is internationally recognised as the most appropriate methodology to estimate the environmental impacts of products, processes, and services and to evaluate the effectiveness of sustainability strategies to reduce them. The objective of this dissertation is to support the European Space Agency (ESA) by developing a cradle-to-grave LCA screening study on an ESA's space-tracking terminal based in New Norcia (AU). The study carried out using the *SimaPro* software assesses various components of the system, including the tracking antenna and the solar panels. Lastly, the overall environmental impacts of the station along its entire life cycle are assessed. The results of this LCA study are used by ESA to hypothesize more sustainable eco-design solutions such as building new solar panels, improving their energy efficiency and producing electricity using wind currents. Indeed, one of the ESA's primary aims carried out by the results of this LCA study is to reduce the environmental impacts related to energy consumption.

Specifically, this dissertation is divided into three main chapters. First, a summary of sustainable development concepts in the space sector is explored. Where, the contributions that the ESA can make to sustainable development and the main actions undertaken by the agency to achieve the set objectives are reported. The second chapter presents the LCA methodology and describes the main software used to carry out an LCA, by providing more details on the software used in this dissertation. In the last chapters, the ESA's case study is analysed. In particular, after introducing the site, the LCA methodology is applied with the aim of assessing its potential environmental impacts. The data and results are reported following the structure of the LCA methodology used and multiple scenarios are compared with the aim of evaluating the strengths and weaknesses of the site. Finally, conclusions, possible alternatives, and future development scenarios are discussed.

RATIONALE & GOALS

Sustainable development and eco-friendliness are today a paramount requirement for all industrial activities and the space industry is no exception, even if space applications provide a unique and essential data collection service (Castiglioni et al., 2015; Maury et al., 2020).

For instance, as highlighted during the COP 21, satellite observations are essential for evaluating the Earth's climate using a series of indicators provided by the instruments in orbit (Maury et al., 2020; Petiteville et al., 2015). In the past, the space sector may has shown a lack of commitment in reducing environmental impacts (Castiglioni et al., 2015), but in recent years there has been a clear turnaround by major space agencies. Specifically, in 2019, the member states of the United Nations Committee for the Peaceful Uses of Outer Space (UN COPUOS) have reached an agreement through the stipulation of a series of guidelines for long-term sustainability of space applications with the aim of reducing their environmental impacts (Maury et al., 2020; United Nations Office for Outer Space Affairs, 2019a). Following the indications provided in these agreements and with the aim of coping with the increase in space activities and the growing number of stakeholders in this sector, it has been possible to develop and promote technologies that minimize environmental impacts and maximize the use of renewable resources (Maury et al., 2020). To support the identification of the technologies which pose lower environmental impacts, the space industry has begun adopting the Life Cycle Assessment methodology (LCA) to assess the full environmental impact of its products and practices throughout their entire life cycle (Maury et al., 2020; Morales, 2019; Wilson & Vasile, 2017).

In this context, a collaboration was born between the European Space Agency (ESA), “Ca' Foscari” University Foundation and the spin-off of the “Ca’ Foscari” University of Venice, GreenDecision S.r.l., which led to the development of a LCA screening study to assess the environmental impacts caused by the agency's ground-based satellite tracking system.

Indeed, the purpose of this dissertation is to evaluate the main environmental impacts caused by the agency's ground-based satellite tracking system and subsequently to support the agency in the assessment of eco-design and sustainable development scenarios. The developed scenarios analyse the different components of the station and how they affect the environment.

STRUCTURE

This thesis is divided into four main chapters. Chapter 1 “The Sustainable Development in the Space Sector”, developed in three sub-chapters, defines the theoretical concept related to the case study and the ESA’s contribution to sustainable development. Chapter 2 “Life Cycle Assessment Methodology”, composed of three sub-chapters, establishes the conceptual development of the LCA methodology. Sub-chapters 3.1 and 3.2 compose Chapter 3 “New Norcia Space-Tracking Station – Materials and Methods”. In these sub-chapters, the application of the LCA methodology to the case study is reported. Lastly, in Chapter 4 “New Norcia Space-Tracking Station – Results”, developed in two sub-chapters, the results of the evaluation of the case study are reported. Finally, conclusions and final considerations are reported. Within the first main chapter, Chapter “1.1 The concept of Space Sustainability” describes the evolution of the concept of sustainable development in the space sector from the publication of the Brundtland commission report up to the most recent period. Furthermore, ESA's contributions to sustainable development linked to Agenda 2030 are reported. Chapter “1.2 ESA Framework Policy on Sustainable Development” contains extracts on the ESA sustainability report and their main initiatives aimed at developing sustainable and environmentally friendly missions. Chapter “1.3 The future challenges for the European Space Agency” exposes ESA's future goals relating to the orbital sector and how ESA sets out to mitigate space debris’ issues. Subsequently, in the second main chapter, Chapter “2.1 Definition” reports the definition of the LCA methodology. Chapter “2.2 Structure of a Life Cycle Assessment” describes in detail the phases of the methodology. In Chapter “2.3 The software for Life Cycle Assessment analysis” the software used to perform this LCA study is presented. Furthermore, Chapter “3.1 New Norcia European Space Tracking (ESTRACK) ground station” provides information about the site of the case study. In Chapter “3.2 Life Cycle Assessment of New Norcia ground station” the data and the results of the case study are reported following the phases and procedures envisaged by the LCA methodology. Lastly, Chapter “4.1 Life Cycle Impact Assessment” exposes the assessment of the environmental impacts that are generated. In Chapter “4.2 Life Cycle Interpretation” the results of the case study are analysed. Finally, the dissertation ends with the “Conclusions” chapter in which possible alternatives and future development scenarios that are more sustainable and with lower environmental impacts are discussed.

1 THE SUSTAINABLE DEVELOPMENT IN THE SPACE SECTOR

In this first chapter, the concept of space sustainability and its evolution is introduced. In particular, the connection between space and sustainable development and the goals set by the Committee on the Peaceful Uses of Outer Space are described. Subsequently, the European Space Agency (ESA) Framework Policy on Sustainable Development and the main ESA's initiative to reduce environmental impacts are reported. Lastly, the ESA's biggest issue about orbital debris is disserted.

1.1 The concept of Space Sustainability

The concept of space sustainability has emerged in the last 15 years to refer to a set of concerns relating to outer space as an environment for carrying out space activities safely and without interference (Schrogl et al., 2015; United Nations Office for Outer Space Affairs, 2019b). Furthermore, it refers as well to concern about ensuring continuity of the benefits derived on Earth from the conduction of such space activities (Schrogl et al., 2015; United Nations Office for Outer Space Affairs, 2021). Moreover, the transition to a low-carbon and resource-efficient circular economy is a political pillar of the European Union and a priority for space agencies (European Space Agency, 2017). Indeed, the space industry is pursuing sustainable development practices to reduce the environmental impacts related to the various activities they perform, just like any other industry. The concept of sustainable development was first expressed in 1987 in the Brundtland report, "which one must call surprisingly prescient for the time when it was written" (Hoerber et al., 2019). In the report the fragility of Earth and its ecosystems was described, as well as its brittleness to anthropogenic impacts. The human being therefore has the duty to preserve the goods granted to it and allow posterity to benefit from them (United Nations, 1987). From these concepts, a more structured definition of sustainable development was then expressed (Hoerber et al., 2019):

"Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (United Nations, 1987).

The connection between space and sustainable development first emerged in an analysis of the utility of space for sustainable development (Hoerber et al., 2019), and it was later suggested that space must be considered as a "global common" because entails common heritage and use (United Nations, 1987). For this reason, in order to reduce the environmental impacts associated with the various activities carried out in orbit and on ground, space industry has begun to adapt to sustainability standards just like any other industry (Hoerber et al., 2019). Accordingly, it is no longer be possible to consider acceptable the emissions and the other environmental impacts associated which space activities, even if they are carried out for the common good of all humanity. This may require a change of mindset oriented towards integrated sustainable development (environmental, social and governance) (Hoerber et al., 2019).

Indeed, the transition to a low-carbon and resource-efficient circular economy is now a priority for many European countries and a political pillar of the European Union (EU) (European Space Agency, 2017). This goal was carried over in the recently published guidelines of the Committee on the Peaceful Uses of Outer Space (United Nations Office for Outer Space Affairs, 2019b). This publication states clearly: “intergovernmental organisations should take into account the social, economic and environmental dimensions of sustainable development” (European Space Agency, 2017; United Nations Office for Outer Space Affairs, 2017). It states that intergovernmental organisations “should promote the development of technologies that minimize the environmental impact of manufacturing and launching space assets and that maximize the use of renewable resources and the reusability or repurposing of space assets to enhance the long-term sustainability of those activities” as well (United Nations Office for Outer Space Affairs, 2018). International agencies such as ESA have been working on this sustainable transformation for years with remarkable results (European Space Agency, 2017).

Therefore, the United Nations Committee on the Peaceful Uses of Outer Space (UN COPUOS) was established in 1959 to regulate activities related to the space sector. The Committee is the principal international forum for the development and codification of laws and principles governing activities in outer space. This Committee currently comprises 95 member states and a large number of permanent observers (Schrogl et al., 2015). During the 60 years of its existence, the deliberations in COPUOS have resulted in several very positive developments to advance international cooperation in the peaceful uses of outer space (Martinez, 2020, 2021; Schrogl et al., 2015).

Since its inception, the committee has concluded five international treaties governing space-related activities (Martinez, 2020; Schrogl et al., 2015):

- *Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies* (1967);
- *Agreement on the Rescue of Astronauts, the Return of Astronauts and the Return of Objects Launched into Outer Space* (1968);
- *Convention on International Liability for Damage Caused by Space Objects* (1972);
- *Convention on Registration of Objects Launched into Outer Space* (1976);
- *Agreement Governing the Activities of States on the Moon and Other Celestial Bodies* (1984).

The 1967 Outer Space Treaty laid the general legal foundation for the peaceful uses of outer space and provided a framework for developing the law of outer space. The four other treaties deal more specifically with certain concepts contained within the 1967 Outer Space Treaty (Martinez, 2020; Schrogl et al., 2015).

Although several aspects of the work of COPUOS are directly relevant to space sustainability, a more holistic approach to the concept of sustainability in the space sector has emerged only in 2005. In that year Karl Deutsch, ex-president of Scientific and Technical Subcommittee (STSC), presented a discussion paper to the Committee on the future role of COPUOS in its next 50 years (Martinez, 2020; Schrogl et al., 2015). Deutsch made the link between the sustainability of life on Earth and the international cooperative use of space systems (Martinez, 2020; Schrogl et al., 2015). Only five years later, in 2010, the STSC established the Working Group on the Long-Term Sustainability of Outer Space Activities under the chairmanship of Peter Martinez (Martinez, 2020; Schrogl et al., 2015).

Most recently, in June 2019 the member states of the UN COPUOS have adopted the new 21 main guidelines for the long-term sustainability of outer space activities (United Nations Office for Outer Space Affairs, 2019a). The guideline 20 of this agreement refers to the development and promotion of technologies that minimise the environmental impact of manufacturing and launching space assets by maximising the use of renewable resources to enhance the long-term sustainability of space activities (Maury et al., 2020; United Nations Office for Outer Space Affairs, 2018). However, it must be stated that in terms of materials' volume, the space sector has a lower consumption in comparison to other industrial sectors (Maury et al., 2020). In addition, ESA has established a common eco-design framework for the European space sector (European Space Agency, 2019b), including the development of tools and systems to evaluate the environmental impact and legislation compliance of programmes (European Space Agency, 2017, 2019b).

1.1.1 European Space Agency's contribution to Sustainable Development

As previously mentioned, space sector and sustainability are deeply connected thanks to a wide range of programmes that will help achieve the Sustainable Development Goals (SDGs) by 2030. The 17 SDGs, which in turn include 169 targets, are collected in the Agenda 2030 for Sustainable Development, an action program for people, planet and prosperity signed in September 2015 by the governments of the 193 member countries of the United Nations. A recent joint study conducted by United Nations Office for Outer Space Affairs (UNOOSA) and the European Global Navigation Satellite System Agency (GSA) found out that, of the 169 targets underlying the goals, nearly 40% are reliant on access to space science and technology (Di Pippo, 2019). Indeed, satellite data and space applications, as well as space technologies, play a major role in addressing issues ranging from health care and education to climate change and human migration (European Space Agency, 2018b).

ESA's contributions for sustainable development include several SDGs. ESA focuses on long-term technology development and aims to maintain the viability of Europe's space industry through continuous innovation (SDG 9) and responsible production methods (SDG 12) (European Space Agency, 2018b). Its activities in this area range from air biofiltration, car thermal protection shields, and heat pipes for electronics, camera tracking for precision automobile assembly and many others (European Space Agency, 2018b). Just to give an example, the *MELiSSA* project (Micro-Ecological Life Support System Alternative) targets nine SDGs and aims to convert organic waste and carbon dioxide into oxygen, water, and food by using light to promote biological photosynthesis (European Space Agency, 2018b). This project can help as well improving the living conditions of people on Earth through the provision of food (SDG 2) and clean water (SDG 6). In addition, ESA's activities include satellite telecommunications and space-based applications for use on Earth (European Space Agency, 2018b). Thanks to these applications, ESA can contribute to monitoring European air quality, developing telemedicine and tele-education systems, assessing future crop yield, managing aviation safety, and assisting with disaster relief (SDGs 2, 3, 4, 5, 13 & 15) (European Space Agency, 2018b).

The support that the space sector can provide for sustainable development is therefore undeniable. To maximize the benefits for the environment, several actors in the space industry, among which ESA, have identified Life Cycle Assessment (LCA) as the most appropriate methodology to address and reduce their environmental impact (Durrieu & Nelson, 2013). In addition to that, ESA has experimented and continues to experiment various eco-friendly initiatives that contribute to increasing sustainability in all its forms, such as the *Clean Space* initiative described in *Chapter 1.2.1.* To justify these initiatives, it is necessary to develop environmentally friendly space policies and programs to promote technological innovations and make the space industry more competitive (Durrieu & Nelson, 2013).

1.2 ESA Framework Policy on Sustainable Development

At ESA, sustainable development is a challenge that has been taken up at corporate level since 2009. The aim is becoming more sustainable while integrating social, environmental and governance concerns at every level (European Space Agency, 2020b). The basic principles governing the framework policy on sustainable development concern (European Space Agency, 2020b):

- answering the needs and expectations of European Member States facing the global challenges of the 21st century;
- strengthening internal and external cooperation and creating synergies on issues of common interest and concern by allowing awareness and knowledge sharing on sustainable development issues;
- preserving resources of all kinds.

Following a dialogue with the internal and external stakeholders, seven main categories were identified to map the Agency's various activities, stakes, and challenges. These were plotted on a graph named "materiality matrix", shown in *Figure 1.1*, where each category represents a domain of action under ESA's activities. To prioritise the actions needed to address those objectives, all stakeholders ranked the categories and stakes according to their level of needs and expectations of ESA, based on all relevant criteria among which the economic performance, environmental matters, and wellbeing (European Space Agency, 2020b).

In the ESA's materiality matrix, environmental concerns like the monitoring and the mitigation of environmental impact on sites and infrastructures or like the programmes about Earth's ecosystem dynamics appear as delicate challenges (European Space Agency, 2020b). Therefore, the main actions of ESA will concern the environment issues at sites and infrastructures as well as on space missions and the creation of a sustainable supply chain. To cope with this, working groups of experts from ESA and industrial partners were set up to define a common approach and establish sector-level consensus on these topics (European Space Agency, 2020b).

Figure 1.1 - ESA's materiality matrix (European Space Agency, 2020b)

The Agency developed the *Framework Policy on Sustainable Development*, endorsed in 2010, which integrated dedicated commitments and goals for three major areas of action: Programme Activities, Environment & Energy, and Governance & Ethic. Following the endorsement of the

Agency's framework, considerable progress has been made in the environmental field (European Space Agency, 2020b). Among these, noteworthy were the targets reached and, in two cases, significantly exceeded, of the *2020 Climate and Energy Package* of European Union. The 2020 package is a set of laws issued to ensure the EU meets its climate and energy targets for the year 2020 starting from 1990 levels (European Commission, 2009; European Parliament, 2009). The package sets three key targets (European Parliament, 2009):

- 20% cut in greenhouse gas emissions;
- 20% of EU energy from renewables;
- 20% improvement in energy efficiency.

The objectives of the 20% reduction in greenhouse gas emissions and 20% increase in use of renewable energy were exceeded respectively by 11% and 39%, but only the 4% of the 20% improvement in energy efficiency objective was achieved (European Space Agency, 2020b). Numerous coordinated actions and local initiatives have been undertaken to meet this objective thanks to various technical improvements such as:

I. the implementation of more efficient lighting systems;
II. the installation of heat-insulated windows;
III. the creation of insulation for roofs and facades;
IV. the enhancement of heating and cooling systems.

ESA has a role to play as an enabler of technology development to decrease the environmental footprint of this sector. Indeed, in-house knowledge and technology developed for space are generally thought to be the most efficient and less demanding in terms of energy while allowing the best rates of recyclability (European Space Agency, 2020b).

1.2.1 Clean Space Initiative

The space industry plays a major role in Earth observation in order to provide essential data for the protection of the environment and ecosystems (European Space Agency, 2021). ESA's Clean Space initiative was set up in 2012 to fulfil this task by considering the environmental impact of the entire life cycle of space missions. To maximize the effectiveness of the various operations, Clean Space's activities were divided into 3 main areas (European Space Agency, 2019a):

- eco-design;
- space debris mitigation;
- in-orbit servicing/active debris removal.

In a perspective of sustainable development, Eco-Design is crucial to promote green technologies to understand how much space activities pollute, to identify alternatives to reduce the environmental impacts and to identify alternative processes or technologies that can be used to reduce these impacts (Morales, 2019). In order to analyse the environmental impact of each space project, it is important to assess emissions, resources consumed, and the pressures put on human and environmental health over a mission's life cycle (European Space Agency, 2019b, 2019a).

The Clean Space initiative aims to provide innovative solutions to tackle environmental challenges and turn them into opportunities for the European space sector. To adopt more eco-friendly technologies, ESA is experimenting Eco-Design activities by examining the environmental impacts of space missions and ground infrastructures (European Space Agency, 2020a).

With the purpose of better understanding the environmental impacts of the space sector, ESA has successfully applied LCA. The current LCA frameworks, as set by the European Commission and by the International Organisation for Standardisation (ISO), do not make special provision for the space industry. Space is, after all, a relatively small part of global economic activity. However, the extreme environments that satellites and launchers have to endure oblige ESA to make extra provision that is not necessarily applicable to other industries (European Space Agency, 2020b).

LCA is a methodology of evaluating and quantifying energy and environmental loads and potential impacts associated with a product, process or activity (European Space Agency, 2020a). This methodology will be explained in *Chapter 2*.

As a result, ESA is now following an Eco-Design approach to mitigate its environmental footprint by designing missions and technologies in a more environmentally friendly way without affecting the performance of the space mission (European Space Agency, 2020a). Lastly, the application of this methodology will help reduce waste, energy consumption and the use of hazardous materials that require costly safety procedures and can cause significant environmental impacts (European Space Agency, 2019b).

1.3 The future challenges for the European Space Agency

Regarding the orbital sector, space debris mitigation is the biggest challenge that ESA will have to face in the coming years. The threat posed by space debris is growing and is fundamental implementing projects to decrease and deorbit it. Indeed, although it may be difficult to imagine, Earth's orbit is a limited natural resource: satellites are much more efficient than airplanes for communication, positioning and surveillance purposes and their number in low orbit has increased considerably over the years. Unfortunately, this situation will not last longer if the issue of space debris and overpopulated Earth orbits is not addressed seriously. Space debris is made up of non-functional satellites (23%), upper stages of launchers (18%), functional debris (14%) and fragments (45%) originating from collisions, launcher upper stages and spacecraft explosions (Durrieu & Nelson, 2013). Undoubtedly, satellites will collide increasing the risk of future and further impacts since the number of non-manoeuvrable satellites is high and increasing (European Space Agency, 2018a). Over 34.000 pieces of debris bigger than 10 cm are being tracked (Durrieu & Nelson, 2013; European Space Agency, 2020b). To prevent collisions involving catalogued debris, alert systems for high-risk conjunction events have been developed by space agencies, permitting them to implement avoidance manoeuvres when necessary (Durrieu & Nelson, 2013; Flohrer et al., 2009). In addition to this issue, another problematic challenge for space agencies is space debris remediation (Newman & Williamson, 2018). Unfortunately, technologies for the safe removal of orbital debris are still in an experimental phase and the debris' remediation is missing entirely from the United Nation guidelines. However, there is no corresponding duty on the launching country to remove a satellite or piece of debris from orbit once it has ended its useful life (Newman & Williamson, 2018).

Several experts are working at international level on studying the best actions needed to deal with this problem. One of these is *CleanSat*, a technology project aimed at developing the necessary technologies to support the compliance of future satellites with Space Debris Mitigation requirements (European Space Agency, 2018a).

Furthermore, the most effective means of stabilising the space debris environment is simply the reduction of mass within regions with high densities of space debris (European Space Agency, 2013a, 2015a). Corresponding requirements therefore mandate the avoidance of injection of mission related objects into densely populated regions such as low-Earth orbit (LEO) and geostationary orbit (GEO) (European Space Agency, 2015a). They also request the removal of space systems that interfere with the LEO region not later than 25 years after the end of the mission. This is implemented by either launching into an orbit altitude on which the natural orbital lifetime is short, to reduce the orbital height to such altitudes after the mission, or to re-orbit in a way that no part of the orbit interferes with the LEO region anymore (European Space Agency, 2013a, 2015a).

To solve these issues, Clean Space initiative team will investigate technologies that enable, simplify, and make the compliance of missions with mitigation requirements more efficient and will oversee efforts to comply with this mitigation, seeking to plug current technological gaps in this area (European Space Agency, 2013a, 2015a).

2 LIFE CYCLE ASSESSMENT METHODOLOGY

This second chapter describes the Life Cycle Assessment methodology. Specifically, its definition, the structure and the main software used are briefly discussed.

2.1 Definition

Life Cycle Assessment (LCA) is an objective methodology for assessing potential environmental impacts and resources used during the life cycle of a product, process, or service (International Organization for Standardization, 2021). A complete LCA study starts from examining the extraction and treatment of raw materials, passes through production, use and transport, up to the final disposal or recycling of the product (Farjana et al., 2021).

The LCA analysis evaluates both the impacts directly associated with the system and the indirect impacts through the quantification of inputs, such as raw materials and energy, and outputs in terms of emissions into air, water, and soil (Muralikrishna & Manickam, 2017).

LCA is a standardized methodology according to International Standard Organizations - ISO 14040 and 14044 (European Commission, 2010; Finkbeiner et al., 2006):

- UNI EN ISO 14040 (2021): “Environmental management”, “Life Cycle Assessment”, “Principles and reference framework”. The ISO provides an overview of LCA practices, applications, and limitations.
- UNI EN ISO 14044 (2021): “Life Cycle Assessment”, “Definition” and “Guidelines”. The ISO represents the main support for the practical application of an LCA study, through the preparation, management, and critical review of the life cycle.

Through these standards, the fundamental principles of LCA have been defined, which are:

- Life cycle perspective;
- Attention focused on the environment;
- Relative approach and functional unit;
- Iterative approach: ensures consistency and completeness of the study and results;
- Transparency: to allow a correct interpretation of the results;
- Completeness;

- Priority of the scientific approach: decisions are based on natural sciences. If this is not possible with other scientific approaches (e.g.: social and economic sciences). If even this is not possible, decisions can be based on value choices (Finkbeiner et al., 2006).

2.2 Structure of a Life Cycle Assessment

The Society of Environmental Toxicology and Chemistry (SETAC) defined a first LCA structure in 1990. This society played a fundamental role in the development and application of this methodology. This first version was then modified in 1993. The two structures of the LCA mentioned are shown below in *Figure 2.1*.

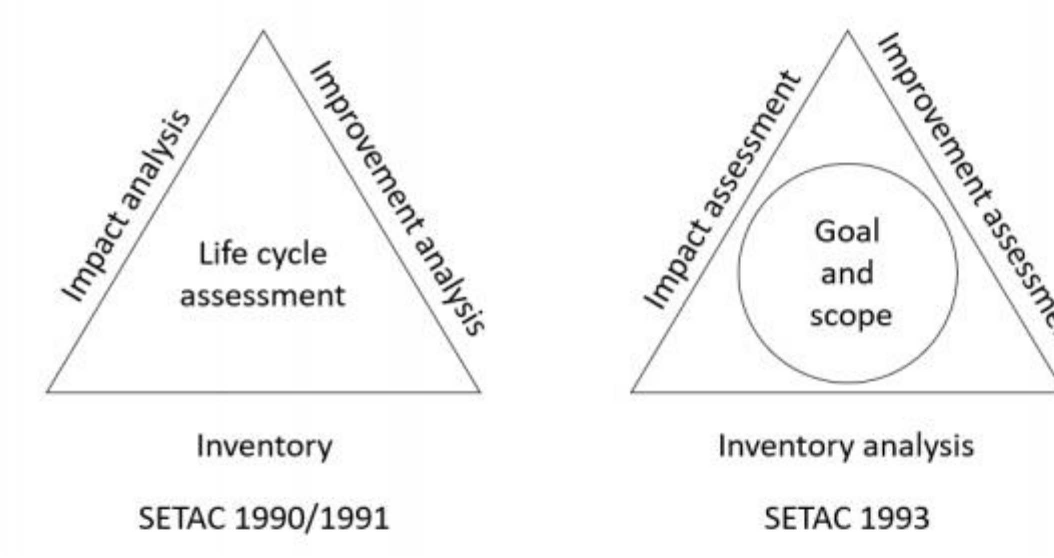

Figure 2.1 - First SETAC LCA structure (Consoli et al., 1994)

Compared to the previous version by SETAC, the ISO 14040 standard defines the current structure of the LCA. The ISO 14040 standard presents the Interpretation phase in place of the Improvement Assessment (Klöpffer & Grahl, 2014).

The phases shown in *Figure 2.2* that constitute an LCA are:

1. Goal and Scope Definition;
2. Life Cycle Inventory (LCI) analysis;
3. Life Cycle Impact Assessment (LCIA);
4. Interpretation of results (Life Cycle Interpretation).

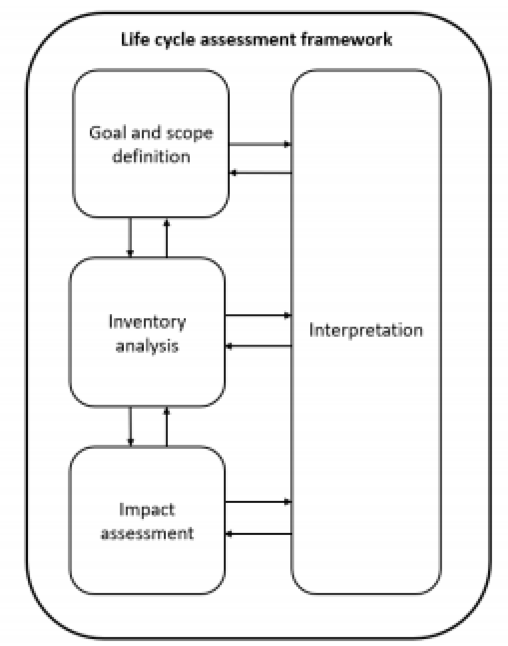

Figure 2.2 - Current LCA structure defined by ISO

2.2.1 Definition of the objective and field of application

In the first phase, the objectives of the study are clearly defined establishing the expected application, the starting goal, and the public to whom the results must be communicated (International Organization for Standardization, 2021). Furthermore, the functional unit and the system boundaries are defined at this stage (European Commission, 2010).

By functional unit it means the reference unit with which to treat and display the data of an LCA, which is chosen based on the purpose of the study. The definition of an appropriate functional unit is essential as it allows comparing the results of an LCA with those relating to other studies (Finnveden et al., 2009). It is sufficient to distinguish between two fundamental aspects, such as the duration of use over time and the extent of the actual function provided, to choose the functional unit for many products (European Commission, 2010).

While as far as the boundaries of the system these must be defined through a meticulous description of the system in all its phases through the construction of a graphical representation of the relevant life cycle processes named flowchart. In this way, it is possible to plan the collection of the necessary data and information that delineate the field of action (European Commission, 2010).

Finally, the quality of the data is of fundamental importance as it affects the reliability of the study results and it can be measured using the following criteria:

- time coverage;
- geographic coverage;
- technological coverage;
- accuracy;
- completeness;
- representativeness;
- consistency;
- reproducibility;
- the data sources;
- information uncertainty.

2.2.2 Inventory Analysis (LCI)

The life cycle inventory involves the compilation and quantification of inputs (resources) and outputs (emissions) of matter and energy through the different stages of the life cycle of a product or service, thus building a flowchart of the system to be analysed (International Organization for Standardization, 2021).

This phase involves an iterative procedure that leads to an in-depth knowledge of the system. Therefore, it will be possible to formulate new requirements or limitations regarding the data. Furthermore, it will also be possible to modify the data collection procedures to achieve the objectives of the study.

In this phase, the data collection takes place. According to the ISO 14040 standard, it would be advisable to prefer the use of primary data, which is collected directly in the field but, very often, the data for the system is missing. For this reason, several databases have been built over the years to facilitate the inventory phase, thus replacing the missing data (Finnveden et al., 2009). The public databases available are national, regional, industrial or consultant based. National and regional databases are used in every Life Cycle Assessment, as they provide data on electricity, raw materials, transport, and disposal services, often based on average data, “which represent average conditions of production and supply of goods and services” (Finnveden et al., 2009).

During the inventory analysis phase, it may be necessary to carry out the allocation procedure that allows to divide the incoming and outgoing flows of a unitary process of the analysed system. However, ISO 14044 recommends avoiding allocation by reviewing the system boundaries, excluding process units that are not relevant or for which the data are insufficient and including other units relating to co-products. When the allocation is unavoidable, it is necessary to refer to the physical quantities (mass, energy, volume, etc.) or, alternatively, to the economic value of the products.

2.2.3 Impact Assessments (LCIA)

The main phase of a Life Cycle Assessment is the assessment of the environmental impacts that are generated as a result of the consumption of resources and their release into the environment. In this phase, the data of the previous phase are characterized on the basis of their potential effects on the environment and "aggregated to support interpretation" (European Commission, 2010; Finnveden et al., 2009). The inventory data is then associated with specific environmental impact categories and category indicators.

The assessment of the impacts is divided into the following phases (European Commission, 2010):

- Classification: provides for the assignment of the inventory results to the chosen impact categories. The impact categories may vary depending on the assessment method that you choose to use but commonly involve the consumption of resources and emissions into the environment.
- Characterization: provides for the quantification of environmental impacts. The results of the inventory analysis are converted, using internationally recognized characterization factors, into indicators with common units of measurement.
- Normalization: process that allows the comparison between the results obtained for the various impact categories and a reference value, which can be the global, regional, and local impact, the impact per inhabitant or the alternative scenario.
- Weighing: multiplication of the result of the indicators by a particular numerical factor, which expresses the relative importance attributed to the different types of impact, depending on the criticality. However, even in this case different evaluations can lead to very different results for the same system.

The first two phases, classification, and characterization, are mandatory, while the normalization and weighing phases are not universally accepted as they could be vitiated by subjective evaluations.

There are several methods that are used to set up each phase of an LCA in practice, among the most common in Europe are:

- Eco-indicator 99;
- EPS 2000;
- EDIP 97;
- IMPACT 2002+.

Another of the most used methods is *ReCiPe*, which aims to transform the long list of results of the life cycle inventory into a limited number of indicators, which allow expressing the relative severity of the category of environmental impact. *ReCiPe* uses two levels of indicators: midpoint and endpoint. The relationship between these two impacts categories is shown below in *Figure 2.3* (Huijbregts et al., 2017; PRé Consultants, 2016).

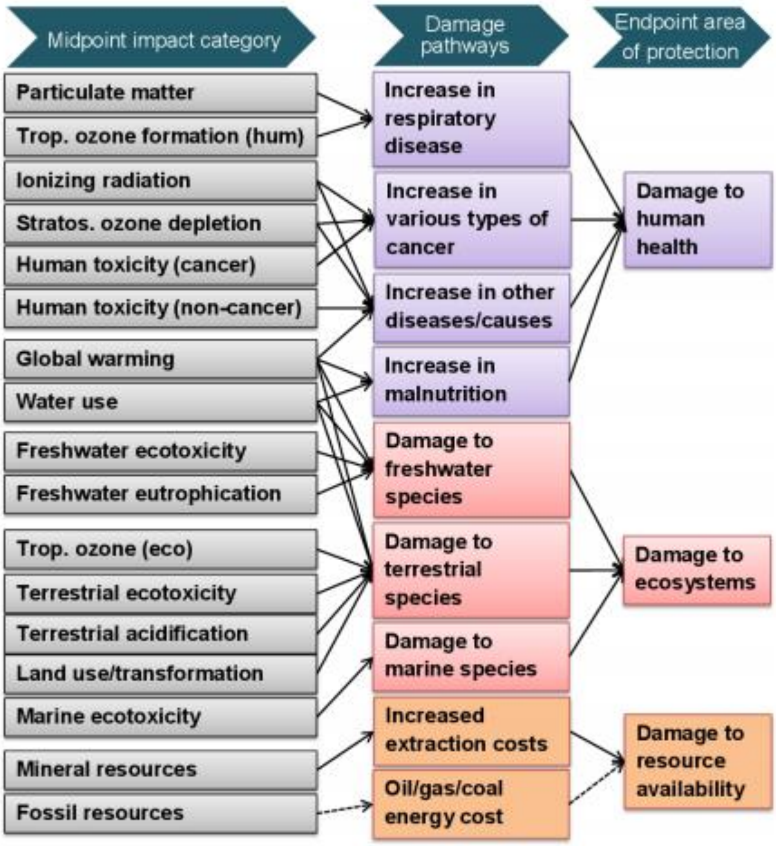

Figure 2.3 - Relationship between midpoint and endpoint indicators in the ReCiPe method (Huijbregts et al., 2017)

The midpoint and endpoint *ReCiPe* method was used to assess the potential environmental impacts. This method has three different versions that do not claim to represent archetypes of human behaviour, but they are merely used to group similar types of assumptions and choices that also differ in the time horizon considered in the impact analysis (PRé Consultants, 2021; Pré Sustainability, 2020):

- Individualistic perspective (I) - 20 years: is based on the short-term interest, impact types that are undisputed, technological optimism as regards human adaptation;
- Hierarchist perspective (H) - 100 years: is based on the most common policy principles with regards to time-frame and other issues;
- Egalitarian perspective (E) - 1000 years: is the most precautionary perspective, taking into account the longest time-frame, impact types that are not yet fully established but for which some indication is available.

The Hierarchist perspective version (H), which expresses an intermediate time horizon (100 years) and conditions in general average compared to the other two versions available in *ReCiPe*, (Individualistic perspective – (I), Egalitarian perspective – (E)) is considered "the perspective" by default (PRé Consultants, 2016) as the best trade-off between extremes. According to the *ReCiPe* method, the results can be reported to two different levels of indicators. The first level can be reported at the midpoint level through 18 impact categories represented in *Table 2.1*:

Table 2.1 - Overview of the midpoint categories and related impact indicators (Huijbregts et al., 2017)

IMPACT CATEGORY	INDICATOR	UNIT	MIDPOINT CHARACTERIZATION FACTOR	ABBREVIATION	UNIT
CLIMATE CHANGE	Infra-red radiative forcing increase	W×yr/m^2	Global warming potential	GWP	kg CO_2 to air
OZONE DEPLETION	Stratospheric ozone decrease	ppt×yr	Ozone depletion potential	ODP	kg CFC-11 to air
IONIZING RADIATION	Absorbed dose increase	man×Sv	Ionizing radiation potential	IRP	kBq Co-60 to air
FINE PARTICULATE MATTER FORMATION	PM2.5 population intake increase	kg	Particulate matter formation potential	PMFP	kg PM2.5 to air

IMPACT CATEGORY	INDICATOR	UNIT	MIDPOINT CHARACTERIZATION FACTOR	ABBREVIATION	UNIT
PHOTOCHEMICAL OXIDANT FORMATION: ECOSYSTEM QUALITY	Tropospheric ozone increase (AOT40)	ppb.yr	Photochemical oxidant formation potential: ecosystems	EOFP	kg NOx to air
PHOTOCHEMICAL OXIDANT FORMATION: HUMAN HEALTH	Tropospheric ozone population intake increase (M6M)	kg	Photochemical oxidant formation potential: humans	HOFP	kg NOx to air
TERRESTRIAL ACIDIFICATION	Proton increase in natural soils	yr×m^2 ×mol/l	Terrestrial acidification potential	TAP	kg SO_2 to air
FRESHWATER EUTROPHICATION	Phosphorus increase in fresh water	yr×m^3	Freshwater eutrophication potential	FEP	kg P to fresh water
HUMAN TOXICITY: CANCER	Risk increase of cancer disease incidence	-	Human toxicity potential	HTPc	kg 1,4- DCB to urban air
HUMAN TOXICITY: NON-CANCER	Risk increase of non-cancer disease incidence	-	Human toxicity potential	HTPnc	kg 1,4- DCB to urban air
TERRESTRIAL ECOTOXICITY	Hazard-weighted increase in natural soils	yr×m^2	Terrestrial ecotoxicity potential	TETP	kg 1,4- DCB to industrial soil
FRESHWATER ECOTOXICITY	Hazard-weighted increase in fresh waters	yr×m^3	Freshwater ecotoxicity potential	FETP	kg 1,4- DCB to fresh water
MARINE ECOTOXICITY	Hazard-weighted increase in marine water	yr×m^3	Marine ecotoxicity potential	METP	kg 1,4- DCB to marine water

IMPACT CATEGORY	INDICATOR	UNIT	MIDPOINT CHARACTERIZATION FACTOR	ABBREVIATION	UNIT
LAND USE	Occupation and time-integrated transformation	yr×m^2	Agricultural land occupation potential	LOP	m^2 ×yr annual crop land
WATER USE	Increase of water consumed	m^3	Water consumption potential	WCP	m^3 water consumed
MINERAL RESOURCE SCARCITY	Ore grade decrease	kg	Surplus ore potential	SOP	kg Cu
FOSSIL RESOURCE SCARCITY	Upper heating value	MJ	Fossil fuel potential	FFP	kg oil

The second level can be reported at the endpoint level, in which the midpoints are aggregated into three categories that assess the overall damage to Human health (DALY), Ecosystems (species.yr) and Resources (USD2013). In general, the assessment of potential impacts at the endpoint level determines results that are easier to interpret and communicate, but which is associated with greater uncertainty. In the analyses carried out in this thesis, all the impacts will be reported both at the midpoint and at the endpoint level.

2.2.4 Interpretation of results

Eventually, in the last phase, the results are considered as a whole and analysed based on the accuracy of the data and considering the assumptions made in the previous phases. Therefore, the results of the inventory analysis and impact assessment are combined. The interpretation phase must provide consistent results with respect to the defined objective and scope, the conclusions reached, limitations and recommendations. The interpretation phase then allows answering the questions posed in the goal and scope definition phase (European Commission, 2010).

The interpretation phase can generate an iterative review process when the requirements defined in the first phase of the LCA are not met. In particular, the phases defined by the ISO 14044 standard are the following:

- identification of the most significant contributions based on the results;

- evaluation of the methodology and results considering the parameters of completeness, sensitivity and consistency;
- conclusions, highlighting limits and recommendations.

The following analyses can be applied to perform the interpretation phase (Klöpffer & Grahl, 2014):

- uncertainty analysis;
- sensitivity analysis;
- analysis of contributions;
- inventory analysis.

2.3 The software for Life Cycle Assessment analysis

The development of an LCA analysis is not possible unless a specific software is used. This software record and process the data, starting from the attribution of the material and energy flows leaving the system to the different categories of impact, up to the use of characterization models for the assessment of impacts on the environment.

The choice of the software to be used for the development of the LCA must refer to the objective of the study, as well as to the performance characteristics of the program, its adaptability, areas of application and the reliability of the results. Generally, a software must operate quickly and easily, without errors. A hierarchical structure is preferable, which allows the analysis system to be divided into different subsystems and offers a clear and transparent representation of the process and the results obtained, in order to guarantee the possibility of identifying any errors or critical issues.

There are several reference software in the European panorama, such as:

- SimaPro (Holland);
- Gabi and Umberto (Germany);
- OpenLCA.

In addition, with the software, numerous European and international databases have been developed containing information directly usable for the inventory phase, some integrated with specific software, as in the case of *Ecoinvent* with *SimaPro*, which are in any case compatible with most of the applications on the market. Other databases, on the other hand, are totally autonomous, such as BUWAL and ETH (both Swiss). Starting from July 2006, on the initiative of the European Commission, a public database was produced online, ELCD, already used in the most recent versions of software tools such as GaBi.

2.3.1 SimaPro software

SimaPro (System for Integrated Environmental Assessment of Products), created in 1990 by the Dutch company PRé (Product Ecology Consultant), is one of the most popular LCA analysis software in the world, used in over 80 countries. It is a reliable tool that allows to collect, monitor, and analyse the environmental performance of products and services, examining even complex life cycles, according to the guidelines of the ISO 14040 series (PRé Consultants, 2016).

It allows carrying out an in-depth modelling of materials and processes, to identify the elements of greatest impact and work on the optimization of the most critical processes, in order to improve their environmental performance. The main features of this software are flexibility in application and modelling, the intuitiveness of the interface and the possibility of having different databases.

SimaPro interfaces with various European databases; this allows to have a large number of data available and therefore the possibility to choose the process or material closest to the one to be examined. Within the common database, the materials and processes are classified according to their content (building materials, energy, transport, etc.) thus allowing easy comparison between similar processes. Among the available databases there is the *Ecoinvent 3* database, the most updated with over 4000 processes. This database, published by the "Swiss Centre for Life Cycle Inventories", contains international inventory data on industrial processes related to energy supply, resource exploitation, and supply of materials, chemicals, metals, agriculture, waste management services and transport (Wernet et al., 2016).

3 NEW NORCIA SPACE-TRACKING STATION – MATERIALS AND METHODS

In this third chapter, the specific case study discussed in this dissertation will be presented. After a general introduction on the site, the chapter will follow the division of the phases of a Life Cycle Assessment to simplify the presentation. The rationale of this evaluation, the application and the inventory phase are presented.

3.1 New Norcia European Space Tracking (ESTRACK) ground station

ESA's tracking station network (ESTRACK) is a global system of ground stations providing links between the European Space Operations Centre (ESOC), located in Darmstadt (Germany), and satellites (Doat et al., 2018; European Space Agency, 2013b). The sites are located in different places around the World in order to maximize the observable area of space. This latter sites have several tasks such as (eoPortal, 2021; European Space Agency, 2013b):

- communicate with spacecraft;
- transmitting commands and receiving scientific data;
- spacecraft status information.

The ESTRACK network was established in 1975 for the *International Ultraviolet Explorer* mission whose goal was to make observations from comets to quasars in the ultraviolet (European Space Agency, 2003, 2013b). Indeed, in the seventies ESA started to deploy its 15 meters antennas around the world. The first to be built was the station located at Villafranca del Castillo, in Spain (Doat et al., 2018; eoPortal, 2021; European Space Agency, 2013b). Every single phase of each mission from special manoeuvres to routine operations is monitored to ensure the success of the missions (eoPortal, 2021; European Space Agency, 2013b). Each station has one or more antenna terminals which include a satellite dish and related radio signal processing equipment (eoPortal, 2021; European Space Agency, 2013b). Using the signals received from space, stations gather radiometric data to support mission controllers know e.g., the location, trajectory and velocity of their spacecraft as well as atmospheric and meteorological data (eoPortal, 2021; European Space Agency, 2013b).

The ESTRACK stations and its associated site infrastructure actually have different functions each (European Space Operations Centre, 2019). Depending on the antenna available, each station can participate in a particular type of space mission. Some of them are located in *Figure 3.1* (eoPortal, 2021; European Space Agency, 2015b):

Figure 3.1 - ESA Tracking Stations Network (ESTRACK). Blue circle indicates core ESA-owned stations operated by the ESTRACK NOC (Network Operations Centre) located at ESA's European Space Operations Centre (ESOC). Orange circle indicates Augmented ESTRACK stations, procured commercially and operated on behalf of ESA by commercial entities. Green circle indicates Cooperative ESTRACK stations owned and operated by external agencies, but regularly providing services to ESA missions on an exchange basis (eoPortal, 2021)

To cope with the expected rapid increase in the number of interplanetary missions, ESA has started building more Deep Space Antennas (European Space Agency, 2013b). The deep space tracking network, part of the ESTRACK core network, consists on a set of three 35 meters class ground stations that are suitable for a wide range of missions as e.g., I) interplanetary missions, II) space astronomy activities, III) solar observation, IV) lunar exploration (Doat et al., 2018; European Space Operations Centre, 2019).

In the 1990s and with the development of a Rosetta-led deep space program, ESA began acquiring a first deep space antenna in New Norcia (AU) (Doat et al., 2018). This ground station will be the focus of the case study explained in this dissertation. The inauguration of this station took place on March 5th in 2003 (Doat et al., 2018). The New Norcia site is located 126 kilometres

North of Perth in Western Australia and it occupies an area of 170 m · 190 m (European Space Operations Centre, 2019).

Figure 3.2 - Satellite photo of the New Norcia site (European Space Operations Centre, 2019)

The New Norcia station include two terminal, New Norcia – 1 (NNO-1) and New Norcia – 2 (NNO-2) (European Space Agency, 2015c). In this case study, only the NNO-1 terminal was considered. The antenna is a Cassegrain Beam Wave Guide antenna (Doat et al., 2018), a parabolic antenna where the feed antenna is mounted behind the surface of the concave main parabolic reflector dish and is aimed at smaller convex secondary reflector suspended in front of the primary reflector (Probecom, 2017). The antenna is fitted with a shaped 35 meters parabolic main reflector and a shaped hyperbolic sub reflector in an elevation over azimuth mount (Doat et al., 2018; European Space Agency, 2015c).

Furthermore, in New Norcia station there is a power plant designed to furnish a reliable electricity supply to all power units. It provides a short-break (SB) power supply using diesel generators, and a no-break (NB) power supply using static converters and batteries. The diesel generators supply each 650 kVA within 1-2 minutes after public power failure. In addition, two static converters supply each 600 kVA and the battery capacity allows for a maximum bridging time of 6 minutes (European Space Operations Centre, 2019).

A control centre adjacent to the terminal manages all operational functions. At this centre, there are also emergency fire systems that include rainwater collection tanks that are specially treated with active coal and UV for human consumption and for emergency use. The total storage capacity is approximately 340 m^3 collected from about 700 m^2 of roof surface.

Furthermore, as of 2017, New Norcia station is being powered in part by sunlight, by means to the installation of photovoltaic panels arranged in five double rows (eoPortal, 2021). This information will be explored further in *Chapter 3.2*.

On 29th April 2021, ESA and the Australian Space Agency have announced the construction of a second antenna for communications with deep space. This new model will complement the current antenna and provide support for communications with deep space through the use of a wider spectrum of frequencies (Carrara, 2021). The terminal will be built with recent technologies that use cryogenic cooling at about −263 ° C to allow for a 40% improvement in signal reception. This improvement will allow the antenna to be able to detect weak impulses coming from deep space (Carrara, 2021).

3.2 Life Cycle Assessment of New Norcia ground station

This chapter deepens the phases of the LCA inherent to the case study. The impact assessment was carried out using the *SimaPro* software (version 9.0) described in *Chapter 2.3.1*.

The research was carried out during the thesis internship from April to September 2021 at GreenDecision S.r.l. For the qualitative and quantitative data of the station, a collaboration was started with ESA, which shared data and information on the processes. The data mainly derive from ESA surveys and were subsequently modelled with *SimaPro* software.

3.2.1 Goal and scope definition

The rationale of this LCA is to support the European Space Agency by developing a cradle-to-grave screening study on an ESA's space-tracking station based in New Norcia (AU). The results of this LCA study will be exploited by ESA to hypothesize a more sustainable eco-design for the construction of future space tracking stations. Indeed, the components of the site can be used as benchmark for comparison with different development scenarios that will be proposed by ESA. Moreover, as stated by Thibaut Maury, *"a segment that deserves investigation for space missions is that related to ground activities" (Maury et al., 2020)* and LCA is the most promising methodology for assessing the environmental and energy impacts of this type of infrastructure (Durrieu & Nelson, 2013).

The study is carried out using *SimaPro* software (version 9.0). Among the databases contained in the program, it was decided to utilise *Ecoinvent* (version 3.5). The objects of study are the terminal, the power plant, and the solar panels. The notion "terminal" denotes the antenna and all associated signal processing equipment. The notion "power plant" denotes all backup equipment namely the diesel generators, the batteries, and the modular UPS transformers. Low voltage panels (i.e., mostly copper bars and metallic cabinets with circuit breakers) were initially to be included in the study, but due to the lack of specific data, it was decided to remove them from the assessment. For the same reason, the "OPS Building" operations centre was also omitted from the study due to insufficient data.

In an LCA study, all flows into and out of the system are allocated according to the functional unit. The **functional unit** chosen in this case study is **one year of activity of the station**. The station has a life cycle of about 50 years if all maintenance is considered. The period of activity in which the antenna is communicating with a satellite is called "Pass". On average, during 2020 there were 1142 passes of which 975 passes during the operational phases, 17 passes during tests and simulations and 150 passes under maintenance periods. The choice of this functional unit is supported by a review of scientific articles, which revealed that for ground space-tracking infrastructures the most used functional unit is precisely one year of operation of the station (Castiglioni et al., 2015; De Santis et al., 2018; Maury et al., 2020; Sydnor et al., 2013).

Depending on the objective of the study, the system boundaries delimit the physical environments, operations, and production processes to be considered. This LCA was carried out using a “cradle-to-grave” approach, which means that all the processes used for the functioning of the structure will be quantified, starting from the acquisition of raw materials up to its end of life. The information just provided are summarized in *Table 3.1*.

Many of the data used to carry out this LCA analysis are primary data, kindly provided by ESA. Others, on the other hand, have been estimated from the available data. These data will be presented in the inventory analysis in *Chapter 3.2.2*.

Table 3.1 - Brief information summary

Function	Transmitting and receiving signals to and from space
Functional Unit	One year of station’s activity, 1142 passes on average
System Boundaries	Raw materials, assembly of the terminal, use phase & downstream
Life Cycle	50 years with maintenance

3.2.2 Life Cycle Inventory

The New Norcia station is made up by various components, as mentioned in *Chapters 3.1* and *3.2.1*. *Figure 3.3* shows the flowchart of the case study under assessment which provides information on the materials and processes involved. The individual components of the system will be analysed in the following sub-chapters. For modelling the scenario represented and summarized in the flow chart, the following primary data were requested through an Excel sheet and Power Point slides provided to ESA to be filled in:

- emissions;
- energy and fuel consumed during the construction of the station;
- fuel consumption;
- life cycle of the antenna;
- maintenance procedures;
- mass, quantity and type of components for the power plant;
- mass, quantity and type of components for the solar plant;
- mass, quantity and type of materials for the construction of the antenna;
- mode of transport, mileage and characteristics of the vehicles used;
- procedures and characteristics on disposal;
- voltage, supply and consumption of electricity;
- water consumption.

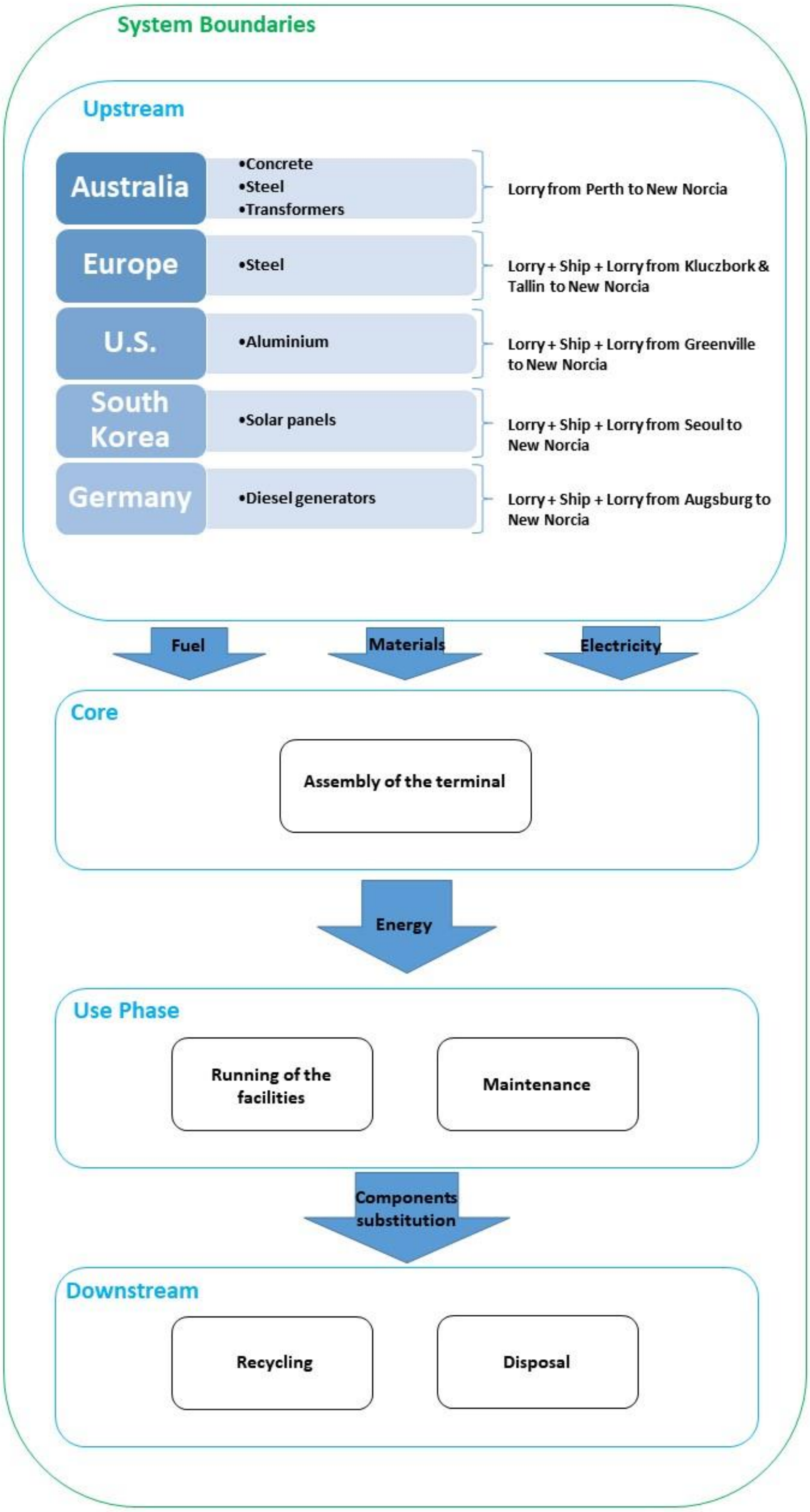

Figure 3.3 - Flow chart of NNO-1

Components insufficiently characterised because of lack of data or data only partially provided were excluded, as already mentioned in *Chapter 3.2.1*. In summary, the following aspects were excluded from the assessment due to lack of data or because they did not fall within the boundaries of the system in question:

- data on employee’s car journeys and fuel consumption;
- low voltage panels;
- cooling machines;
- operative station building (OPS) and its materials;
- travel data concerning maintenance workers;
- employee’s water consumption.

Furthermore, additional information for diesel generators and batteries were retrieved through research in order to correctly modelling the data in the *SimaPro* software. This information is specifically dealt with in the respective paragraphs. Lastly, some assumptions have been made directly by ESA.

3.2.2.1 Antenna

The 35 m antenna of the New Norcia site, shown in *Figure 3.4*, can be divided into three sections:

- upper section (aluminium and steel): the main component of the whole antenna due to its signal reception function;
- middle section (concrete and steel): it has a support function and acts as a counterweight to balance the entire antenna;
- lower section (concrete and steel): it has an important supporting and structural function.

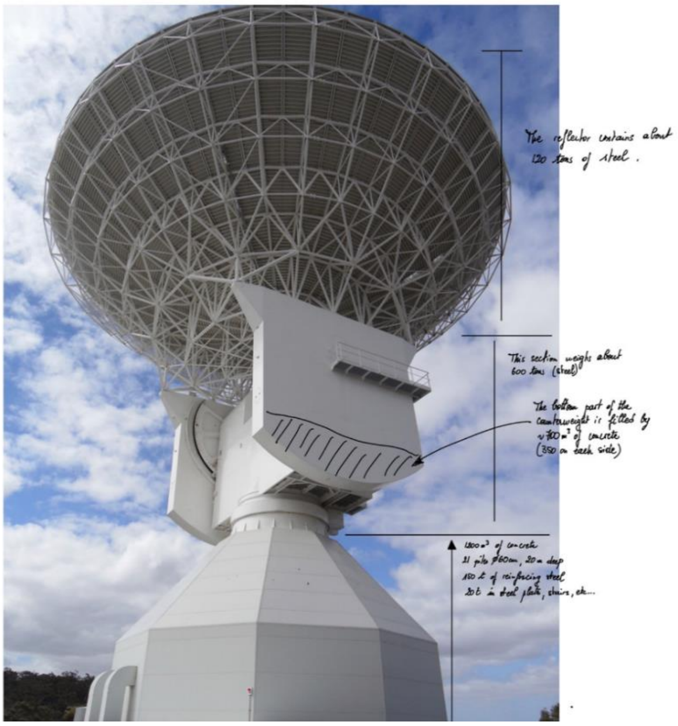

Figure 3.4 - New Norcia 35m antenna

The quantities of the materials used for the antenna construction, the distribution of its components in the three sections and the information regarding their transport to the site are summarized in *Table 3.2*.

Table 3.2 - Antenna components and quantities

Sections	Components	Materials	Amount	Unit	Nation of Departure	Departure Site	Arrival Site	Truck (km)	Boat (km)
Upper	Reflector base	Steel	120	t	Estonia	Tallinn	New Norcia	126	23800
	Reflector panels	Aluminium	15	t	United States	Greenville	New Norcia	686	24700
Middle	Structural components	Steel	450	t	Poland	Kluczbork	New Norcia	576	23150
	Structural components	Concrete	150	t	Australia	Perth	New Norcia	126	-
	Counterweight	Concrete	70	m^3	Australia	Perth	New Norcia	126	-
Lower	Structural components	Concrete	1200	m^3	Australia	Perth	New Norcia	126	-
	Reinforcing components	Steel	150	t	Australia	Perth	New Norcia	126	-
	Miscellaneous parts	Steel	20	t	Australia	Perth	New Norcia	126	-

With the purpose to standardize all the data in mass units, the volumetric data of the concrete were converted into tons thanks to the average density value of the concrete (2420 kg/m^3) provided by *SimaPro*, as presented in *Table 3.3*. Furthermore, it should be noted that the data relating to concrete and steel from Perth have been merged into the SimaPro software to simplify the calculation.

Table 3.3 - Concrete conversion from volume unit to mass unit

Sectors	Components	Amount (m^3)	Amount (t)
Middle	Counterweight	70	169.4
Lower	Structural components	1200	2904

The value in tons was obtained according to the formula:

$$Amount\ (t) = \left(Amount\ (m^3)\ \cdot\ 2420\ {}^{kg}\!/_{m^3}\right) \cdot 1000$$

On average, the works lasted 10 hours a day, 6 days a week from 12 December 2000 to 13 November 2001. In total, 482580 L of fuel were consumed for the operation of the building machines.

3.2.2.2 Power plant

The New Norcia's power plant site acts as a backup in the event of a power failure from the main network and includes two diesel generators, sixty $LiFePO_4$ batteries and two modular UPS transformers. Due to the lack of information regarding the masses of these components, additional insights were carried out to identify the most suitable mass value based on the available model. Furthermore, due to the absence of data regarding the nation of departure of $LiFePO_4$ batteries, the Market process was selected on *SimaPro* instead of the Transformation process. This difference is explained in *Chapter 3.2.2.8*.

The quantities of these components, their characteristics, and the information regarding their transport to the site are summarised in *Table 3.4*.

Table 3.4 - Power plant components and values

Components	Amount (Power)	Unit (Power)	Nation of Departure	Departure Site	Arrival Site	Truck (km)	Boat (km)	Amount (Mass)	Unit (Mass)	Sources
Diesel Generators	650	kVA	Germany	Augsburg	New Norcia	900	21850	7650	kg	(Kohler, 2019)
Modular UPS Transformers	600	kVA	Australia	Perth	New Norcia	126	-	1100	kg	(AEG Power Solutions, 2019)
$LiFePO_4$ Batteries	-	-	-	-	New Norcia	-	-	6.5	kg	(Upower, 2016)

The *SimaPro* software does not have available information on the kiloVolt Ampere (kVA) as unit of measurement in its system, but the kiloWatts (kW).

The kVA is the unit of measurement of apparent power, given by the sum of active power (which is measured in kW) and reactive power (kVAR, which is the power produced by the generator that is not used by the load, but which is continuously exchanged between user and generator):

$$\text{Apparent Power (kVA)} = \text{Active Power (kW)} + \text{Reactive Power (kVAR)}$$

The KW (kiloWatt) is the unit of measurement of the active power, the one that can actually be used by a load connected to a generator. Active power is obtained from the apparent total power by multiplying it by the power factor:

$$\text{Active Power (kW)} = \text{Apparent Power (kVA)} \cdot \text{Power factor}$$

In the case of the alternator of a generator, the power factor value is 0.8.

Consequently, a conversion from kVA to kW was carried out to choose from the inventory the most suitable materials for the ESA's components reported in *Table 3.5*.

Table 3.5 - Components power unit conversion from kVA to kW

Components	**Amount (kVA)**	**Amount (kW)**
Diesel Generators	650	520
Modular UPS Transformers	600	480

3.2.2.3 Solar plant

Eight hundred and twenty photovoltaic panels arranged in five double rows compose the solar plant contributing to the on-site production of electricity equal to 35% of the total. The panels are monocrystalline, more expensive to buy initially, but cheaper to install on site.

The quantities of these components, their characteristics, and the information regarding their transport to the site are summarised in *Table 3.6*.

Table 3.6 - Solar plant components and related values

Components	Amount (Power)	Unit (Power)	Nation of Departure	Departure Site	Arrival Site	Truck (km)	Boat (km)	Amount (Mass)	Unit (Mass)
Solar panels	470	MW/h y	South Korea	Seoul	New Norcia	175	9260	17	kg

3.2.2.4 Electricity consumption and production

The station is supplied with electricity from the national grid, while about 35% of the total is produced on site with photovoltaic panels in the solar plant. The power received by the station from the supplier is at 33 kV, but the transformers bring it down to 415 V for the operation of all facilities.

For this study, the total energy consumption in a period of 12 months (September 2017 - August 2018) equal to 1360 MWh/year was considered. Of this amount, the solar plant produces 470 MWh/yr over the same period. Consequentially, only the difference (890 MWh/yr) is officially purchased from the public electricity grid.

3.2.2.5 Fuel consumption

Through the backup system, the station can cope with sudden blackouts of electricity from the grid. Therefore, fuel is purchased to power the diesel generators and is transported by trucks from Perth to New Norcia.

The diesel fuel consumption of the diesel generators is in average 10000 litres per year.

3.2.2.6 Maintenance

Maintenance of all components is essential for maintaining their functionality and ensuring optimal performance. Actually, not many parts are changed. Maintenance mostly includes checking the functions, cleaning parts, and re-adjustments operations. However, the following components are replaced during the entire life cycle of the station:

- $LiFePO_4$ batteries are replaced every 10 years;
- modular UPS transformers are replaced every 20 years;
- the solar panels are replaced every 25 years.

Furthermore, lubricating gearbox oil is used to allow normal operation of the antenna rotation and movement machinery. The average consumption of this lubricating oil is 50 L/yr.

3.2.2.7 Disposal

The end-of-life assumptions were suggested directly by ESA based on the recent disposal of a smaller antenna. Indeed, in December 2015, a 16 meters antenna based in Perth has been decommissioned and sold to the Portuguese government (European Space Agency, 2016). Then, the reflector was dismantled into pieces and shipped over to the Azores where it was rebuilt. The electronic equipment was also removed and shipped over. The concrete structure was scrapped while the ground was restored to its original condition. The company that demolished the pedestal separated the steel from the concrete and both were recycled. A crushing machine separated the concrete, and the resulting concrete pieces were used as substructure for roads and other constructions.

Therefore, also in this case study most of the materials and components of the station were directed to the recycling process. Components such as exhausted batteries and a small percentage of the non-recyclable materials of the solar panels have been directed to different disposal processes after a careful study of the end of life (i.e., pyrolysis and landfill).

3.2.2.8 SimaPro Database and Inventory of New Norcia's items

All identified processes have been selected from the *Ecoinvent* 3.5 database and the system model used is "Cut-off", whose underlying philosophy is that a producer is fully responsible for the disposal of his/her waste and that he/she receives no credit for the supply of recyclable materials (ecoinvent, 2017). Furthermore, the selected processes are of the "System" type in which the calculation times are faster, and all the sub-processes are aggregated into a single process.

In the choice of the different processes, the geographical reference of the data was also considered since each activity present in *Ecoinvent* refers to a specific geographical position. This can refer to the whole world (GLO or RoW), a region made up of several countries (e.g., RER), a country (e.g., AU) or a smaller area (e.g., a province). Whenever possible, the processes referring to Australia were considered for this analysis, which are more suitable for representing the Australian context. Where not possible, the "Global" and "Rest of the World" processes were considered.

All the processes used for this case study are system version processes. The differences between the system and unit processes are summarized in *Table 3.7*. Furthermore, where possible the processes used are of the Transformation type and only some exceptions are of the Market type. Transformation processes contain all the inputs for making a product or service, excluding transport processes, and inputs from all the associated emissions and resource extractions. Market processes include inputs from production in several or a single country and inputs of transport processes. When data from a specific supplier is not known, it is recommended to use the market process (Pré Sustainability, 2021).

Table 3.7 - Differences between unit and system processes (PRé Consultants, 2016)

Unit process	System process
Transparent (but big) process tree, that allows you to trace the contribution of all individual unit processes	Simple process tree
Contains uncertainty information, which allows you to run statistical analysis (e.g., Monte Carlo)	No uncertainty information
Relatively slow calculation	Fast calculation

Table 3.8 shows the *SimaPro* processes used for the components of this case study. All these processes came from the *Ecoinvent* library.

Table 3.8 - SimaPro processes identified as the most suitable for the case studies under assessment

Sector	Original Item	Transformed value per functional unit	Processes	Notes
Terminal	Aluminium	0.3 t	Aluminium, primary, ingot {IAI Area, EU27 & EFTA}| aluminium, ingot, primary, import from Northern America | Cut-off, S	-
	Concrete	64.5 t	Concrete, high exacting requirements {RoW}| concrete production, for building	-

Sector	Original Item	Transformed value per functional unit	Processes	Notes
			construction, with cement CEM II/A | Cut-off, S	
	Steel	14.8 t	Reinforcing steel {RER}| production | Cut-off, S & Reinforcing steel {RoW}| production | Cut-off, S	-
	Building machines	9651.6 L	Diesel, burned in building machine {GLO}| processing | Cut-off, S	-
Power Plant	Diesel generators	0.153 t	Diesel-electric generating set, 650 kVA (0.52 MW) {RER}|	Check at the base of the table[1]

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[1] Due to the absence in the *SimaPro* database of a diesel generator similar to the one present in the New Norcia station, a new process was modelled starting from an existing process. For this propose the "Diesel-electric generating set, 10MW {RER}| diesel-electric generating set production, 10MW | Cut-off, S" was used as a benchmark. The process in question refers to a 10 MW diesel generator, much more performing than the one owned by ESA. Its unit of measure in the software is "p" (i.e.: one piece). Being able to use only processes with units of mass measurement to be able to include them in the disposal scenario on *SimaPro*, it was decided to convert the "p" value into tons. Consequently, knowing the mass and the value in MW of the generator of this case study, the following proportion was set to discover the hypothetical mass of the one present in the *SimaPro* database. Once the mass of the diesel generator on the software was discovered, it was possible to use the newly created process as representative of that of the case study.

$$0.052\,p : 7.65\,t = 1\,p : x$$

$$x = \frac{7.65\,t \cdot 1\,p}{0.052\,p} = 147.115385\,t$$

Sector	Original Item	Transformed value per functional unit	Processes	Notes
	$LiFePO_4$ batteries	0.13 kg	Battery, Li-ion, rechargeable, prismatic {GLO}| market for | Cut-off, S	Process chosen in Market due to the lack of information regarding the origin of the batteries and their transport to New Norcia
	Modular UPS transformers	22 kg	Transformer, low voltage use {GLO}| production | Cut-off, S	-
Solar Plant	Solar panels	0.34 kg	Photovoltaic cell, single-Si wafer {RoW}| 1.6 m · 1 m	Check at the base of the table[2]
Energy	Diesel	10000 L	Diesel {RoW}| petroleum refinery operation | Cut-off, S	-

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[2] Due to the absence in the *SimaPro* database of solar panels similar to those present in the New Norcia station, a new process was created starting from an already existing one. The "Photovoltaic cell, single-Si wafer {RoW}| production | Cut-off, S" process was used as a benchmark. This process refers to a 1 m · 1 m solar panel, while those in possession of ESA are 1.6 m · 1 m. Its unit of measure in the software is "m^2" (i.e.: square metres). Being able to use only processes with units of mass measurement to be able to include them in the disposal scenario on *SimaPro*, it was decided to convert the "m^2" value into kg. Consequently, knowing the mass and the value in "m^2" of the solar panel of this case study, the following proportion was set to discover the hypothetical mass of the one in the *SimaPro* database.

$$1.6\ \mathrm{m}^2 : 17\ kg = 1\ \mathrm{m}^2\ : x$$

$$x = \frac{17\ kg\ \cdot 1\ \mathrm{m}^2}{1.6\ \mathrm{m}^2} = \ 10.625\ kg$$

Once the mass of the solar panel on the software was discovered, it was possible to use the newly created process as representative of that of the case study.

Sector	Original Item	Transformed value per functional unit	Processes	Notes
	Electricity	1360 MWh	Electricity, high voltage {AU}| market for | Cut-off, S	-
	Electricity production	10000 L	Diesel, burned in diesel-electric generating set {GLO}| market for | Cut-off, S	-
Transports	Trucks	Various	Transport, freight, lorry, unspecified {RoW}| transport, freight, lorry, all sizes, EURO3 to generic market for | Cut-off, S	Due to the absence of specific information regarding transport and its characteristics, the general and unspecified process was chosen
	Ships	Various	Transport, freight, sea, transoceanic ship {GLO}| processing | Cut-off, S	Due to the absence of specific information regarding transport and its characteristics, the general and unspecified process was chosen
Maintenance	Gearbox oil	50 L (gearbox oil); Various components	Lubricating oil {RoW}| production | Cut-off, S	Maintenance also includes batteries, transformers and solar panels. These components' processes are the same as mentioned above in the respective sectors of this table

Sector	Original Item	Transformed value per functional unit	Processes	Notes
Disposal	Gearbox oil disposal	-	Spent solvent mixture {RoW}| market for spent solvent mixture | Cut-off, S	-
	Aluminium recycling	-	Recycling of aluminium {GLO}	Process created with the use of the average value of energy necessary for the recycling of aluminium
	Concrete recycling	-	Waste reinforced concrete {RoW}| treatment of waste reinforced concrete, recycling | Cut-off, S	-
	Steel recycling	-	Waste reinforcement steel {RoW}| treatment of waste reinforcement steel, recycling | Cut-off, S	-
	Diesel generators disposal	-	Used diesel-electric generating set, 18.5kW {GLO}| treatment of used diesel-electric generating set, 18.5kW | Cut-off, S	-
	Transformers disposal	-	Used industrial electronic device {GLO}| treatment of,	-

Sector	Original Item	Transformed value per functional unit	Processes	Notes
			mechanical treatment | Cut-off, S	
	Batteries disposal	-	Used Li-ion battery {GLO}| treatment of used Li-ion battery, pyrometallurgical treatment | Cut-off, S	-
	Solar panels recycling	-	Waste electric and electronic equipment {GLO}| treatment of, shredding | Cut-off, S	-
	Solar panels disposal	-	Waste, from silicon wafer production, inorganic {RoW}| treatment of, residual material landfill | Cut-off, S	-

4 NEW NORCIA SPACE-TRACKING STATION – RESULTS

In this fourth chapter, the results of the case study evaluation are presented and discussed. The chapter will follow the division of the last two phases of a Life Cycle Assessment. The assessment of the impacts and, finally, the interpretation of the results are presented.

4.1 Life Cycle Impact Assessment

This chapter presents and discusses the results of the impact assessment. The *ReCiPe* midpoint and endpoint method and *Hierarchist perspective (H)* version were used to assess the potential environmental impacts deriving from the upstream, core and downstream processes. According to the *ReCiPe* method, the results can be reported with respect to two different levels of indicators: at the midpoint level through 18 impact categories (listed in *Chapter 2.2.3*) and at the endpoint level, in which the midpoints are aggregated into 3 categories that assess the overall damage on human health, ecosystems and resources. Midpoint results are more robust as less calculation steps and precise characterization factors are involved in their assessment, nevertheless their interpretation is complex. On the other hand, Endpoint results are less robust as damage conversion involves several approximations, but results are easier to interpret and communicate. In both cases (Midpoint and Endpoint), Normalization has been applied in order to compare results of different indicators, which are otherwise relative to the specific impact. The assessment of the impacts is divided into the phases of classification, characterization, normalization and weighing. In this case study, it was decided to report the characterized and normalized results.

In the next sub-chapters, three scenarios will be illustrated. The first scenario, called “Scenario 0”, represents the real case study. Subsequently, in the last sub-chapter two other alternative scenarios will be presented to illustrate and deepen the differences and peculiarities with respect to the Scenario 0.

The first of these, called “Scenario A”, consists of the Scenario 0 with a hypothetical total recycling of solar panels. The second alternative scenario, which we will call “Scenario B”, consists of the Scenario 0 without solar panels to produce electricity on site and without batteries for energy storage. The purpose of this scenario was to observe the difference in impact resulting from the use of photovoltaic panels belonging to the ESA station. For this reason, a new “Station” group has been created which includes I) Terminal, II) Power Plant (without batteries for B scenario) and III) Photovoltaic (present only in scenarios 0 and A). The new group names for the three scenarios will be as follows: I) Station, II) Energy, III) Transports, IV) Maintenance and V) Disposal. Furthermore, to make the comparison, Scenario 0 has been remodelled by grouping some groups in the “Station” category (Terminal, Power Plant and Photovoltaic).

Figure 4.1 displays the flowchart of the whole LCA study. Line thickness represents relative contribution to impacts from the different processes. On the following pages, the processes of the tree diagram are represented in detail in *Figure 4.2*, *Figure 4.3*, *Figure 4.4*, *Figure 4.5* and *Figure 4.6*.

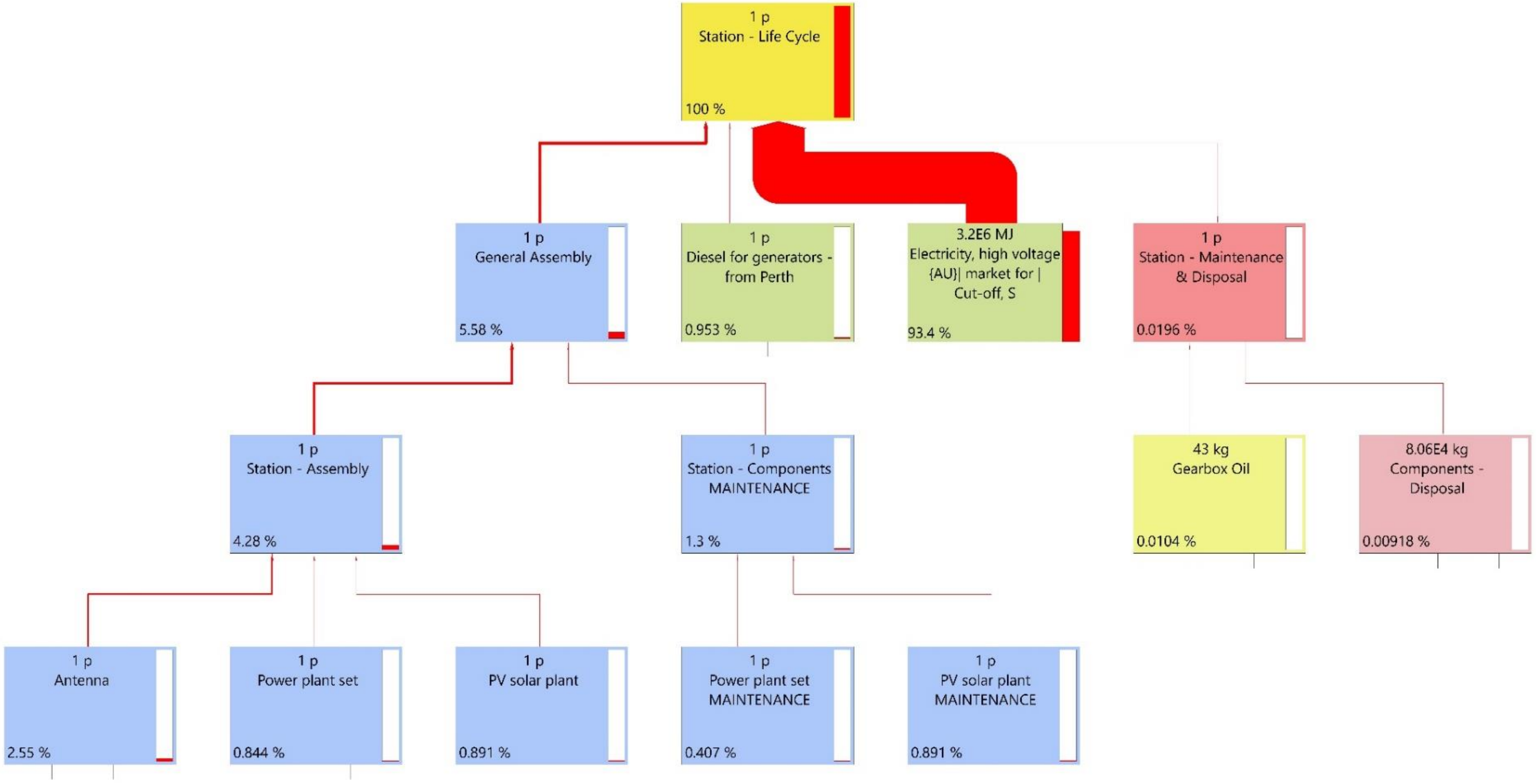

Figure 4.1 - New Norcia Life Cycle Assessment tree diagram

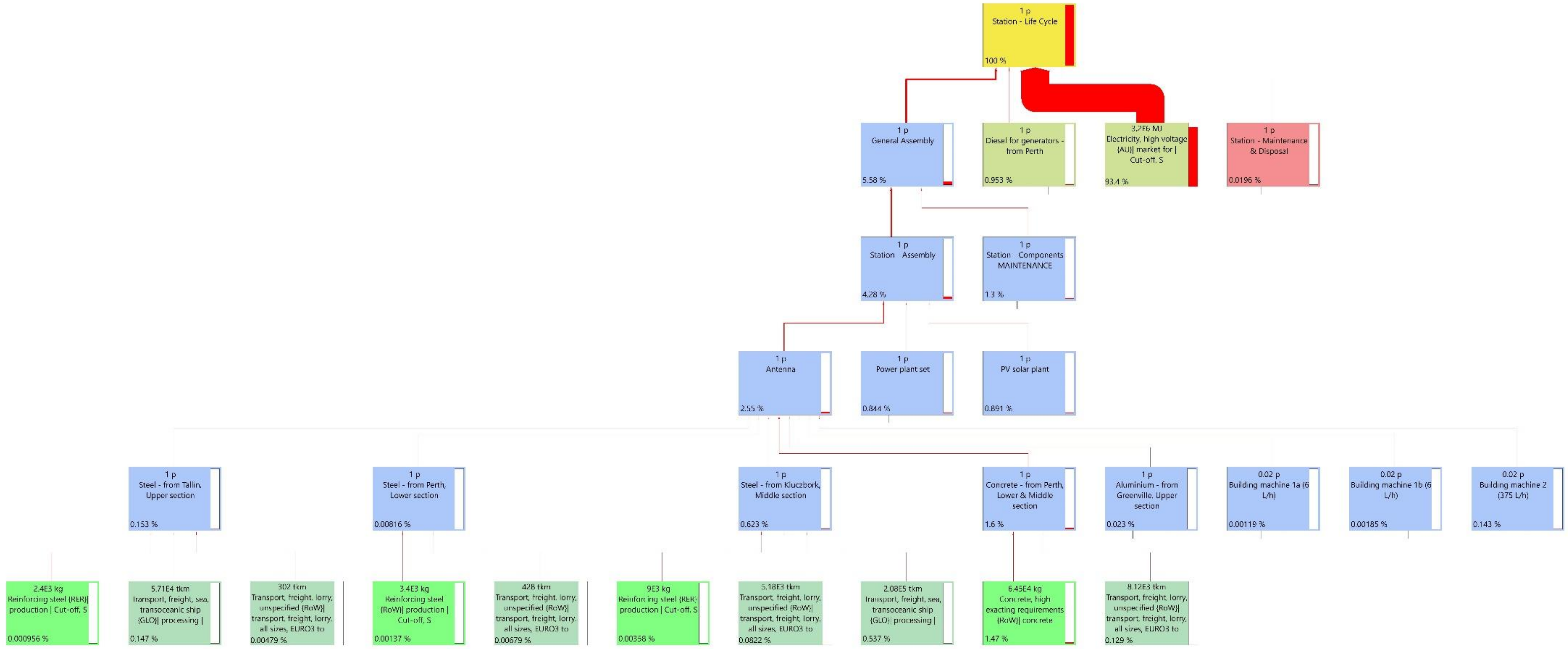

Figure 4.2 - New Norcia Life Cycle Assessment tree diagram: antenna (1)

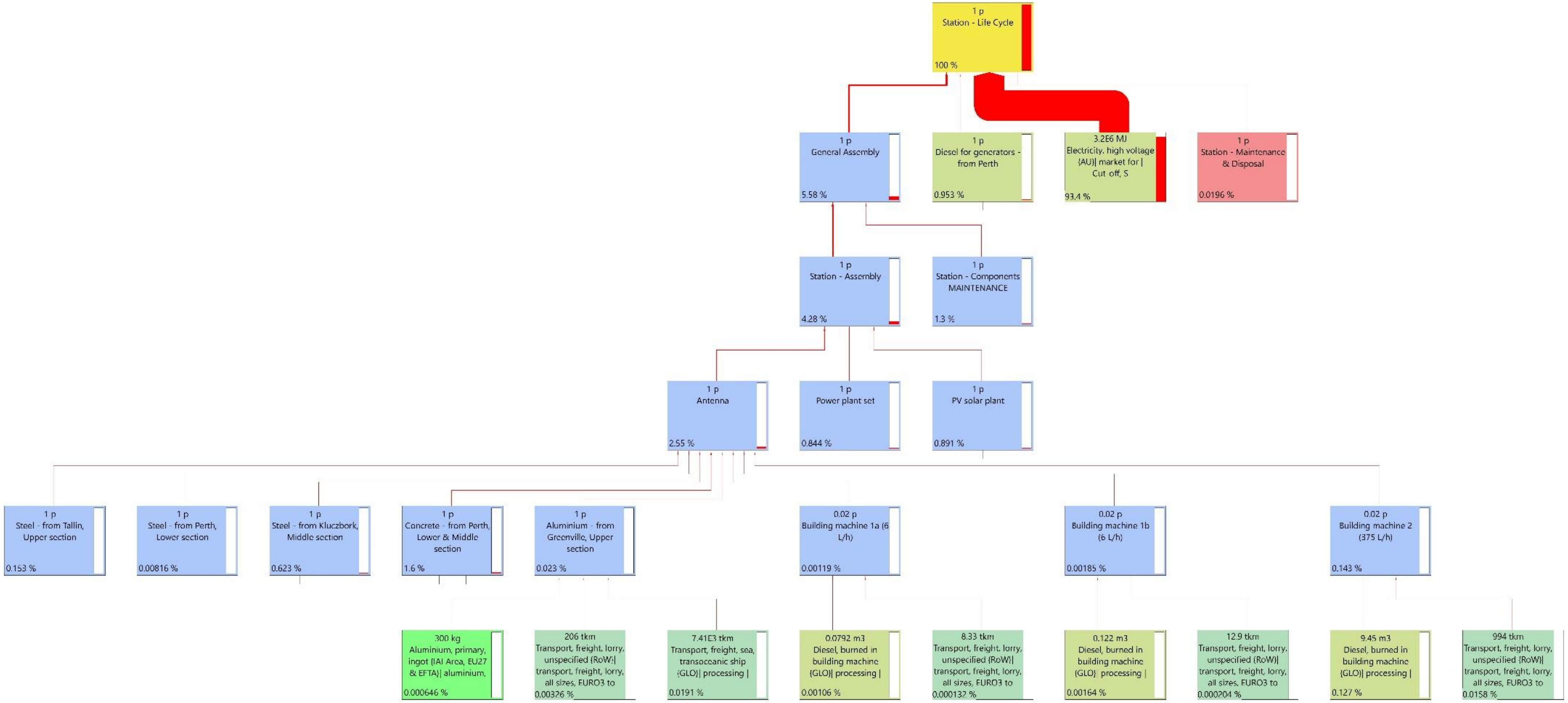

Figure 4.3 - New Norcia Life Cycle Assessment tree diagram: antenna (2)

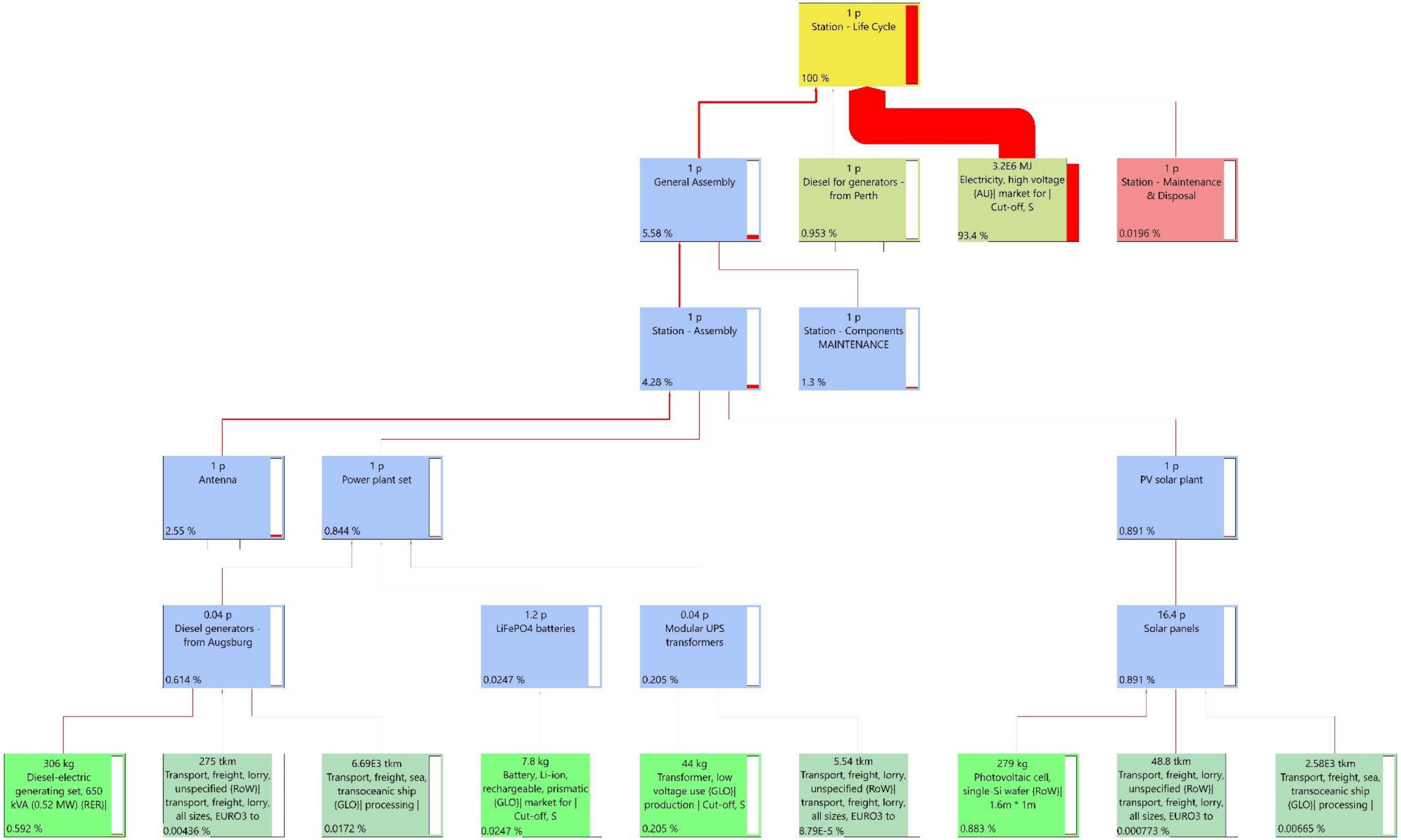

Figure 4.4 - New Norcia Life Cycle Assessment tree diagram: power plant & photovoltaic

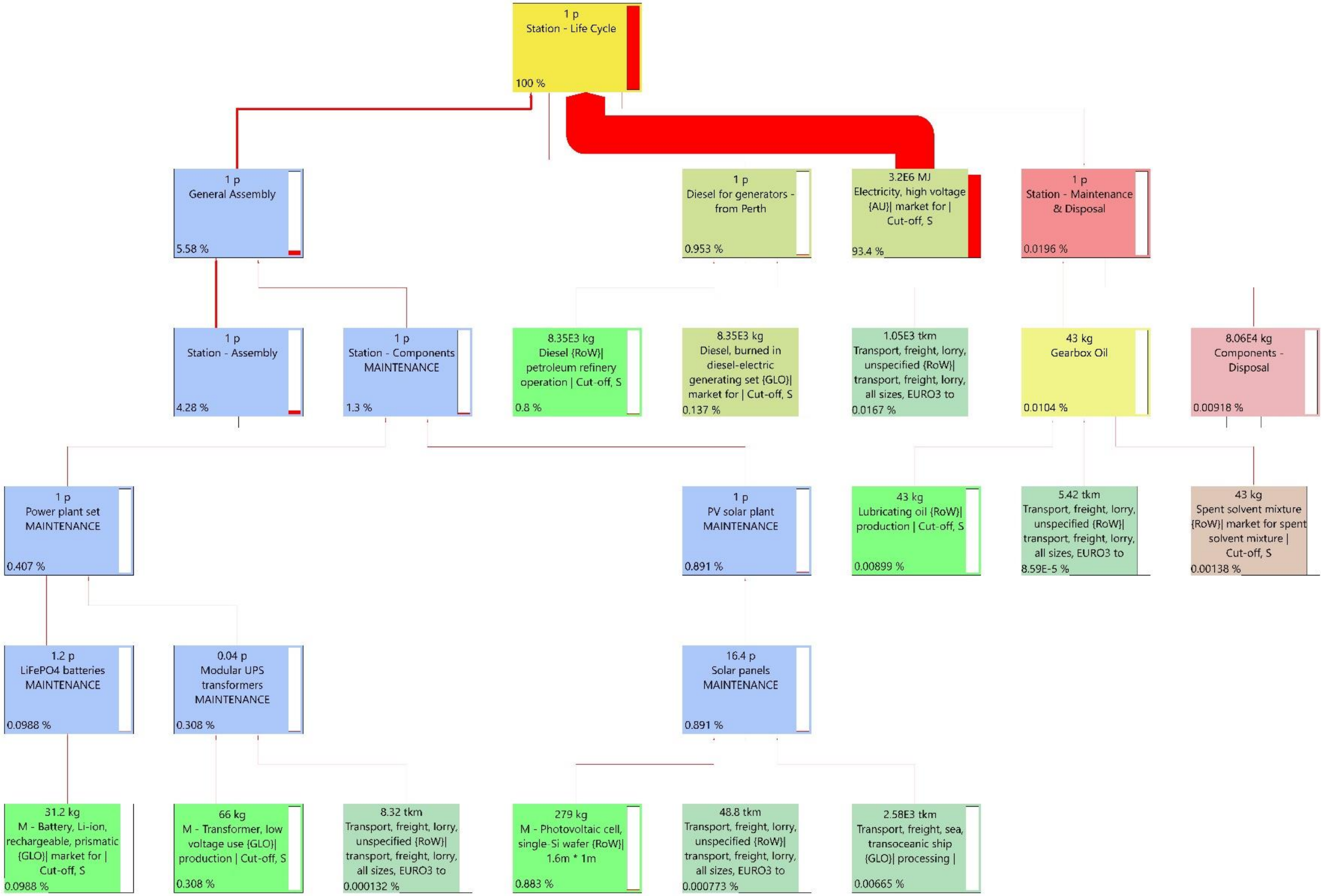

Figure 4.5 - New Norcia Life Cycle Assessment tree diagram: energy & maintenance

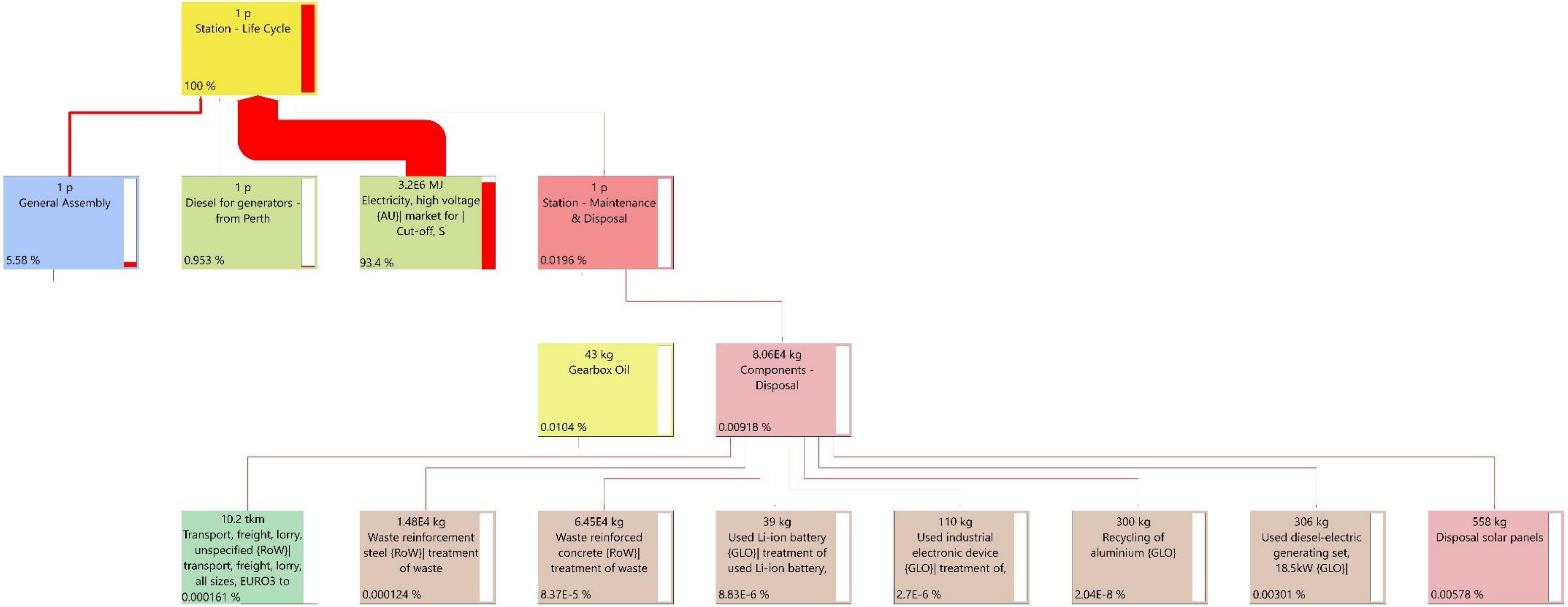

Figure 4.6 - New Norcia Life Cycle Assessment tree diagram: disposal

4.1.1 Scenario 0 LCIA results

In this sub-chapter, the Endpoint and Midpoint results of Scenario 0 will be presented.

4.1.1.1 Endpoint results

Endpoint results provide an overview of damages generated by impacts caused by the different Life Cycle processes of New Norcia station.

As reported in *Table 4.1*, "Energy" is the most impacting group with around 94% of total damage. This information is clear from *Figure 4.7*, in which it can be seen how much the groups affect the different endpoints. Characterization results are obtained by aggregating impacts from processes on the inventory related to each category multiplied by the corresponding characterization factor as defined by the *ReCiPe* method. Characterization results are not comparable as each is in a different unit of measure. *Figure 4.8* shows that the "Human health" endpoint is the most impacted (89.971%). This latter figure represents endpoint results normalized. Normalization shows to what extent the result of an impact category indicator has a relatively high or a relatively low value compared to a reference. The *ReCiPe* recommended reference which has been utilized is the average annual impact of a European citizen in 2010 (National Institute for Public Health and the Environment, 2020). In the following sections, the different groups will be assessed separately with the aims to investigate the rationale of the reported damage level.

Table 4.1 - Scenario 0: endpoint normalization results in percentage

Damage category	Total	Terminal	Power Plant	Energy	Transports	Maintenance	Disposal	Photovoltaic
Total	100.000%	1.603%	0.822%	94.384%	0.998%	1.299%	0.010%	0.883%
Human health (DALY)	89.971%	1.423%	0.790%	84.851%	0.891%	1.203%	0.009%	0.805%
Ecosystems (species.yr)	8.882%	0.150%	0.029%	8.480%	0.078%	0.079%	0.001%	0.065%
Resources (USD2013)	1.147%	0.031%	0.004%	1.053%	0.030%	0.017%	0.000%	0.014%

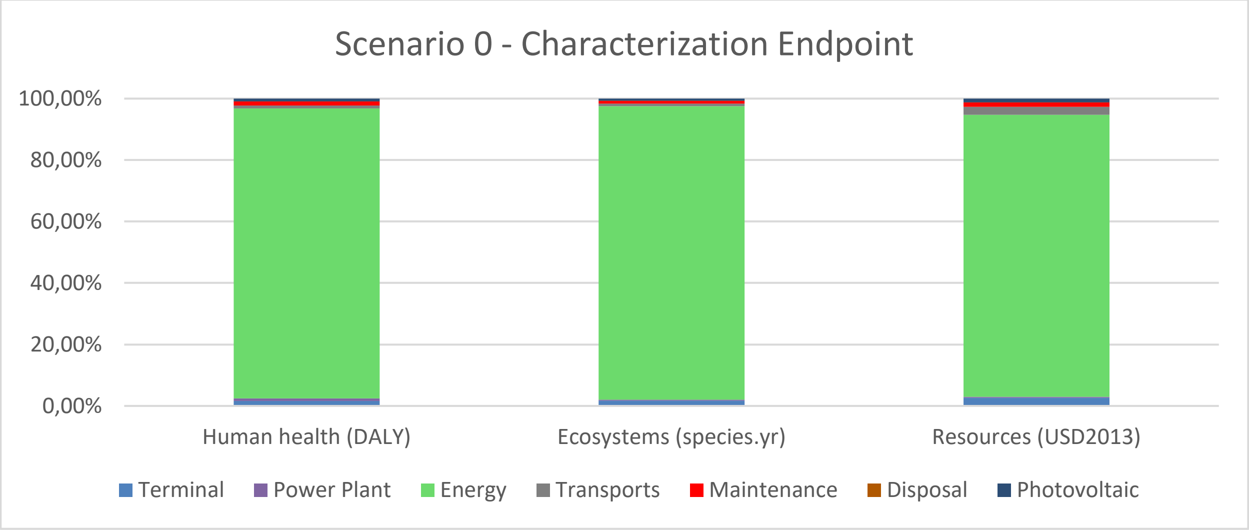

Figure 4.7 - Scenario 0: endpoint characterization results

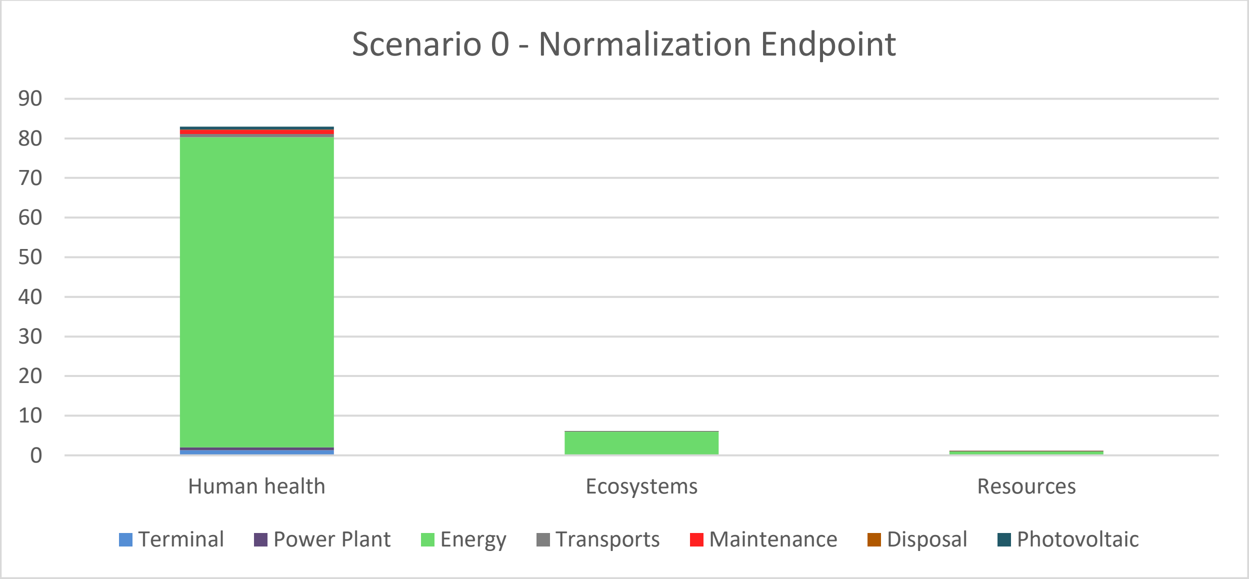

Figure 4.8 - Scenario 0: endpoint normalization results

4.1.1.2 Midpoint results

Midpoint results are more precise than Endpoint results as fewer aggregations took place. Relative results of Scenario 0 are reported for each Impact category and groups in *Table 4.2*. This table represents Midpoint characterization results reported to 100%.

Table 4.2 - Scenario 0: midpoint characterization results in percentage

Impact category	Terminal	Power Plant	Energy	Transports	Maintenance	Disposal	Photovoltaic
Global warming (kg CO_2 eq)	2.102%	0.135%	95.631%	0.614%	0.786%	0.010%	0.722%
Stratospheric ozone depletion (kg CFC11 eq)	0.423%	0.119%	98.122%	0.331%	0.535%	0.004%	0.466%
Ionizing radiation (kBq Co-60 eq)	8.666%	1.791%	47.623%	5.155%	18.877%	0.142%	17.746%
Ozone formation, Human health (kg NOx eq)	2.677%	0.282%	92.006%	3.220%	0.974%	0.010%	0.832%
Fine particulate matter formation (kg PM2.5 eq)	1.734%	0.811%	92.202%	2.138%	1.748%	0.012%	1.355%
Ozone formation, Terrestrial ecosystems (kg NOx eq)	2.694%	0.290%	91.890%	3.230%	1.019%	0.010%	0.868%
Terrestrial acidification (kg SO_2 eq)	1.338%	0.672%	94.042%	2.105%	1.092%	0.008%	0.743%
Freshwater eutrophication (kg P eq)	0.162%	0.373%	98.718%	0.045%	0.443%	0.002%	0.257%

Impact category	Terminal	Power Plant	Energy	Transports	Maintenance	Disposal	Photovoltaic
Marine eutrophication (kg N eq)	0.169%	0.325%	98.284%	0.052%	0.670%	0.003%	0.497%
Terrestrial ecotoxicity (kg 1,4-DCB)	3.176%	13.448%	39.477%	4.358%	23.135%	0.061%	16.346%
Freshwater ecotoxicity (kg 1,4-DCB)	0.455%	2.363%	93.822%	0.146%	1.759%	0.907%	0.548%
Marine ecotoxicity (kg 1,4-DCB)	0.476%	2.466%	93.454%	0.181%	1.953%	0.781%	0.690%
Human carcinogenic toxicity (kg 1,4-DCB)	0.392%	1.443%	96.373%	0.155%	1.203%	0.007%	0.428%
Human non-carcinogenic toxicity (kg 1,4-DCB)	0.490%	2.963%	93.525%	0.178%	2.169%	0.008%	0.666%
Land use (m^2a crop eq)	5.766%	1.172%	82.120%	3.965%	3.755%	0.053%	3.168%
Mineral resource scarcity (kg Cu eq)	19.911%	23.946%	34.628%	1.806%	14.276%	0.049%	5.385%
Fossil resource scarcity (kg oil eq)	1.030%	0.130%	96.511%	0.797%	0.806%	0.006%	0.721%
Water consumption (m^3)	9.970%	0.574%	70.762%	0.693%	9.126%	0.020%	8.856%

As anticipated by Endpoint results, “Energy” is the most impacting group for all categories. However, it should be noted that in the categories “Ionizing radiation”, “Terrestrial ecotoxicity” and “Mineral resource scarcity” a good percentage of impact is also due to other groups, as can be seen from the *Figure 4.9*. This latter figure represents Midpoint characterization results reported to 100%. Characterization results are obtained by aggregating impacts from processes on the inventory related to each category multiplied by the corresponding characterization factor as defined by the *ReCiPe* method. Characterization results are not comparable as each is in a different unit of measure, because of this *Figure 4.9* columns should not be compared each other. For this instance, only relative contributions within each column can be evaluated.

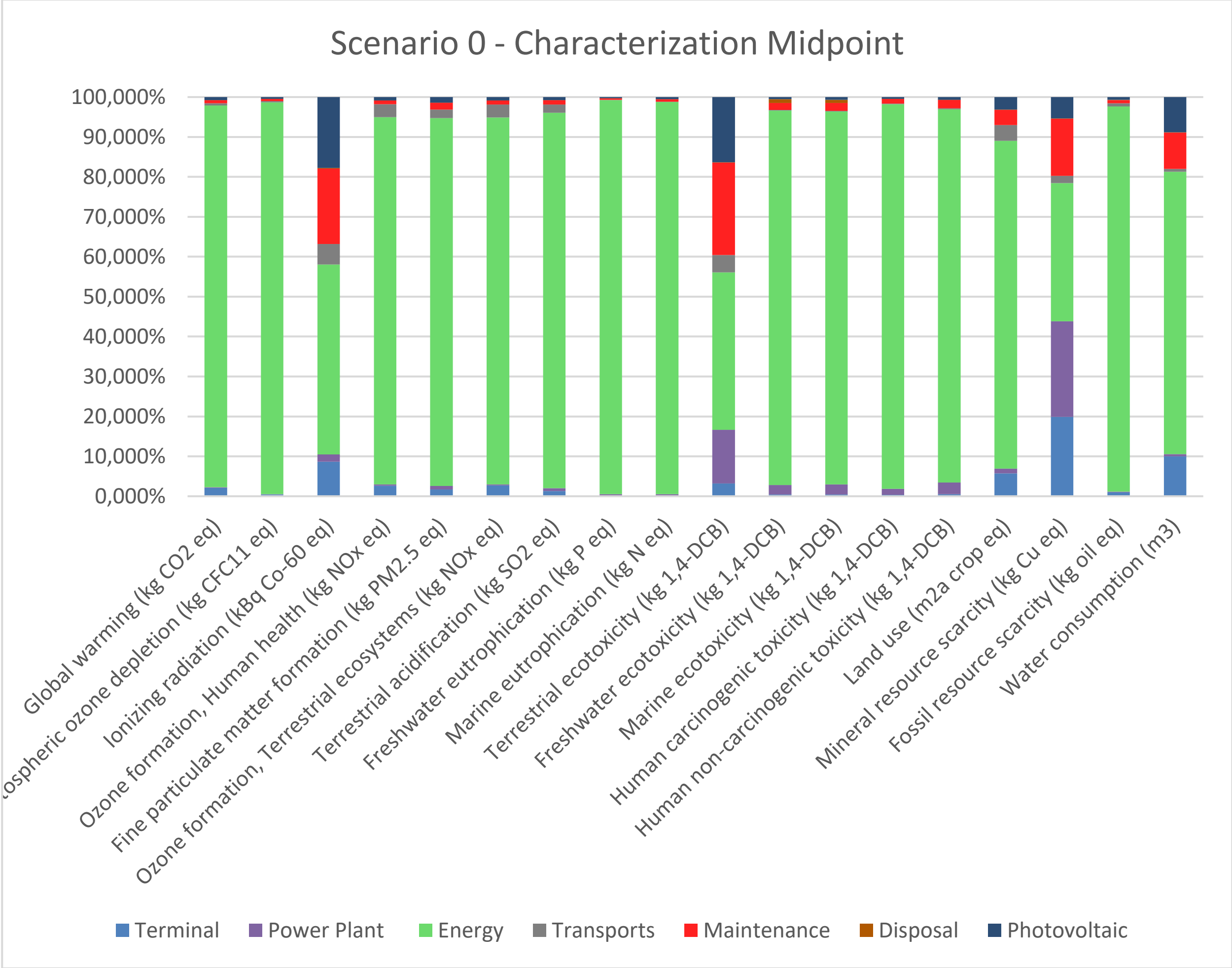

Figure 4.9 - Scenario 0: midpoint characterization results

For most of the midpoint indicators, “Energy” is what drives the impacts due to the large amount of electricity used for the normal operation of the station every year. For “Ionizing radiation”, “Terrestrial ecotoxicity”, “Mineral resource scarcity”, “Land use” and “Water use” indicators there will be a more detailed discussion in the following subsections as the impacts are also driven by other factors.

In *Figure 4.10* it is possible to observe the normalized results. Normalized results denote a predominance in impacts to “Freshwater ecotoxicity”, “Marine ecotoxicity”, “Human carcinogenic toxicity” and “Human non-carcinogenic toxicity”.

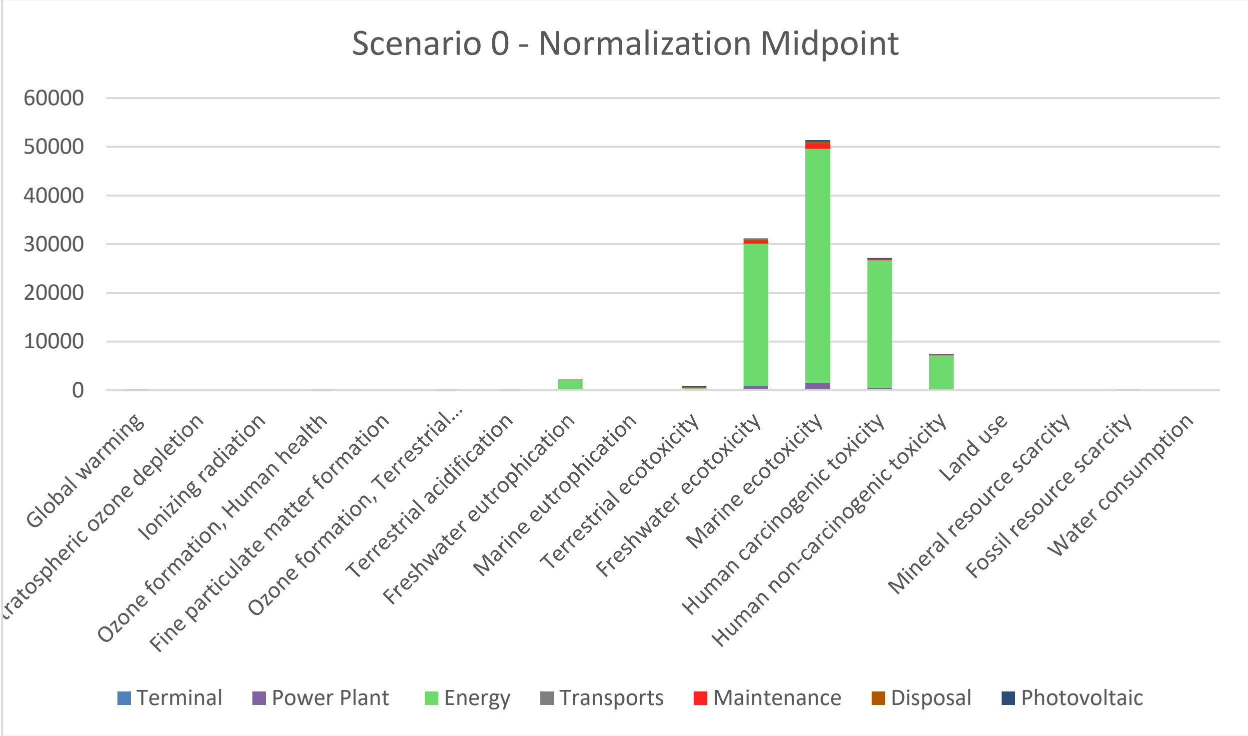

Figure 4.10 - Scenario 0: midpoint normalization results

The results of the normalization assessment show that “Energy” is the cause of the impacts of the midpoints “Freshwater ecotoxicity”, “Marine ecotoxicity”, “Human carcinogenic toxicity” and “Human non-carcinogenic toxicity”.

The characterization results of each Midpoint category assessed are detailed in the following subsections. The impact categories analysed are related to the results of the characterization assessment. All the midpoints’ description will be listed with their relative explanations and measurement units in *Appendix I*.

Ionizing radiation

The ionizing radiation midpoint results are mainly driven by energy consumption (about 47% value). Furthermore, maintenance and photovoltaic panels each contribute approximately 18% to the total impact. The terminal alone has an impact of around 9%. This is due to the type and quantity of minerals extracted for the construction and substitution of mostly solar panels. In addition, concrete is the most impactful material among those used for the construction of the antenna also due to the large quantity used, as the LCA evaluates all direct and non-direct impacts.

Human toxicity and ecotoxicity

The following midpoints are grouped in this section: terrestrial ecotoxicity, freshwater ecotoxicity, marine ecotoxicity, human carcinogenic toxicity and human non-carcinogenic toxicity.

The terrestrial ecotoxicity midpoint results are mainly driven by energy consumption (about 39% value). Furthermore, maintenance, photovoltaic panels and the power plant contribute approximately 23%, 16% and 13% respectively to the total impact. This is due to the type and quantity of minerals extracted for the construction and substitution of solar panels and diesel generators, as the LCA evaluates all direct and non-direct impacts.

The other four midpoint results (freshwater ecotoxicity, marine ecotoxicity, human carcinogenic toxicity and human non-carcinogenic toxicity) are mainly driven by energy consumption.

Land use

The land use midpoint results are mainly driven by energy consumption. However, it can be noted that the terminal alone has an impact of about 5% due to the use of concrete.

Water use

The water use midpoint results are mainly driven by energy consumption. However, it should be noted that the terminal, maintenance, and photovoltaic panels influence by about 10% each due to concrete and solar panels.

Mineral resource scarcity

The mineral resource scarcity midpoint results are mainly driven by energy consumption. However, it can be noted that the terminal, the power plant, and the maintenance have an impact of approximately 20%, 24% and 14% respectively. This is due to the type and quantity of minerals used in the construction of all components. Indeed, the most impacting elements are concrete, diesel generators, transformers and solar panels.

4.1.2 Alternative Scenarios LCIA results

In this sub-chapter, the Endpoint and Midpoint results of Scenarios 0, A and B will be presented.

4.1.2.1 Endpoint results

In this sub-chapter, the scenarios described in *Chapter 4* will be compared in order both to understand how the impacts are distributed in the other designated options and to test whether the use of photovoltaic panels has had a benefit in terms of environmental impact.

All the scenarios illustrated have been reported in percentage after having identified and set the most impactful scenario as the maximum value (100%). Also in this case, as reported in *Table 4.3*, *Table 4.4* and *Table 4.5*, "Energy" is the most impacting group in all scenarios. From the total values, it can be seen that the most impacting scenario is Scenario B, i.e., the scenario without photovoltaic panels and batteries.

Indeed, photovoltaic panels help saving 470 MWh energy per year by decreasing the overall impact compared to the scenario without panels. Furthermore, raw materials, end of life and maintenance of the panels have a lower impact compared to that of energy, as shown in this thesis.

It can also be noted that Scenario 0 has the same values as Scenario A. This is because the only difference present in the Disposal between the two scenarios is minimal and mostly negligible. This difference will be analysed in detail later in *Chapter 4.2*. *Figure 4.11* shows how much the groups affect the different endpoints. The greatest impact of the three scenarios can be seen in *Figure 4.12*. In any case, Scenario B appears to be the most predominant as regards the impacts.

Table 4.3 - Scenario 0: endpoint single score results

Damage Category	**Total**	**Station**	**Energy**	**Transports**	**Maintenance**	**Disposal**
Total_0	67.825%	2.244%	64.016%	0.677%	0.881%	0.007%
Human health (DALY)_0	61.023%	2.046%	57.550%	0.604%	0.816%	0.006%
Ecosystems (species.yr)_0	6.024%	0.165%	5.752%	0.053%	0.054%	0.001%
Resources (USD2013)_0	0.778%	0.033%	0.714%	0.020%	0.011%	0.000%

Table 4.4 - Scenario A: endpoint single score results

Damage Category	Total	Station	Energy	Transports	Maintenance	Disposal
Total_A	67.824%	2.244%	64.016%	0.677%	0.881%	0.006%
Human health (DALY)_A	61.022%	2.046%	57.550%	0.604%	0.816%	0.005%
Ecosystems (species.yr)_A	6.024%	0.165%	5.752%	0.053%	0.054%	0.001%
Resources (USD2013)_A	0.778%	0.033%	0.714%	0.020%	0.011%	0.000%

Table 4.5 - Scenario B: endpoint single score results

Damage Category	Total	Station	Energy	Transports	Maintenance	Disposal
Total_B	100.000%	1.628%	97.487%	0.667%	0.215%	0.003%
Human health (DALY)_B	89.981%	1.485%	87.692%	0.595%	0.207%	0.002%
Ecosystems (species.yr)_B	8.949%	0.121%	8.769%	0.052%	0.007%	0.001%
Resources (USD2013)_B	1.070%	0.023%	1.026%	0.020%	0.001%	0.000%

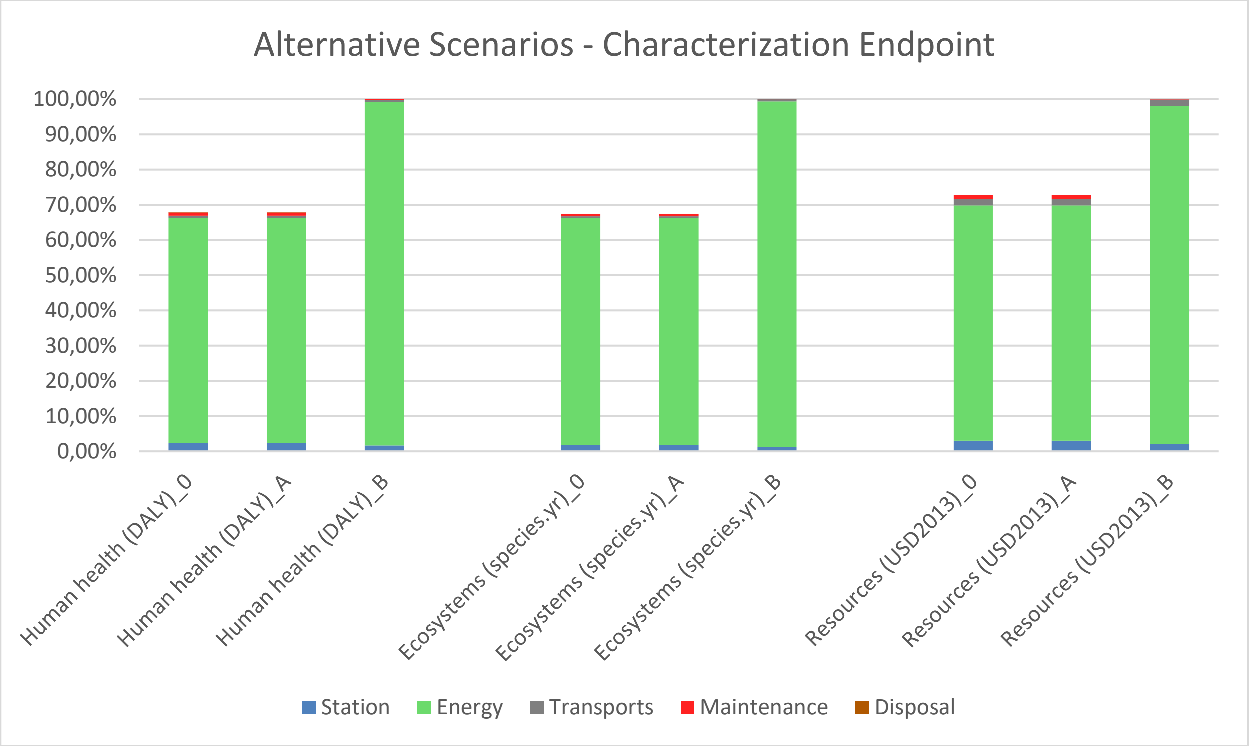

Figure 4.11 - Comparison of the alternative scenarios: endpoint characterization results

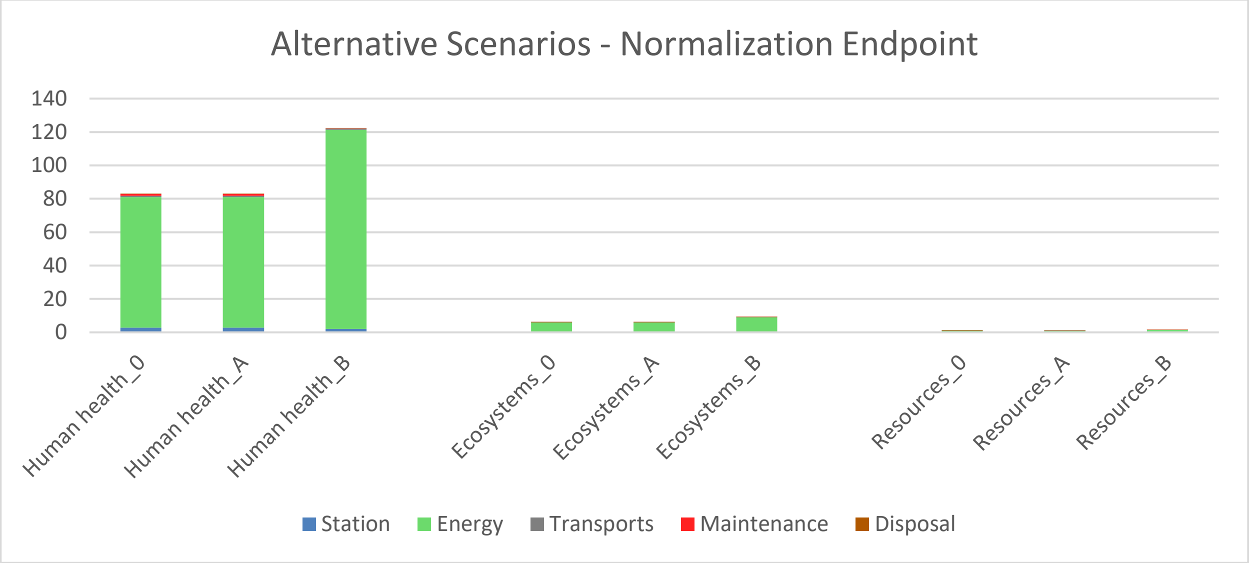

Figure 4.12 - Comparison of the alternative scenarios: endpoint normalization results

4.1.2.2 Midpoint results

Midpoint results are more precise than Endpoint results as fewer aggregations took place. Relative characterization results of the alternative scenarios are reported for each Impact category and groups in *Table 4.6*, *Table 4.7* and

Table 4.8. Please note that the tables below represent the impacts of the three scenarios compared to 100%, therefore only the table of case B (the most impacting case) will have 100% total.

Table 4.6 - Scenario 0: midpoint characterization results

Impact category	Station	Energy	Transports	Maintenance	Disposal
Global warming (kg CO_2 eq)_0	1.990%	64.306%	0.413%	0.528%	0.006%
Stratospheric ozone depletion (kg CFC11 eq)_0	0.671%	65.313%	0.220%	0.356%	0.003%
Ionizing radiation (kBq Co-60 eq)_0	28.202%	47.622%	5.155%	18.877%	0.142%
Ozone formation, Human health (kg NOx eq)_0	2.596%	63.014%	2.205%	0.667%	0.007%
Fine particulate matter formation (kg PM2.5 eq)_0	2.690%	63.600%	1.475%	1.206%	0.009%
Ozone formation, Terrestrial ecosystems (kg NOx eq)_0	2.641%	63.005%	2.215%	0.698%	0.007%
Terrestrial acidification (kg SO_2 eq)_0	1.869%	63.857%	1.429%	0.742%	0.005%
Freshwater eutrophication (kg P eq)_0	0.523%	65.146%	0.030%	0.292%	0.001%
Marine eutrophication (kg N eq)_0	0.657%	65.173%	0.035%	0.444%	0.002%
Terrestrial ecotoxicity (kg 1,4-DCB)_0	32.968%	39.475%	4.358%	23.134%	0.061%

Impact category	Station	Energy	Transports	Maintenance	Disposal
Freshwater ecotoxicity (kg 1,4-DCB)_0	2.274%	63.398%	0.099%	1.189%	0.613%
Marine ecotoxicity (kg 1,4-DCB)_0	2.463%	63.366%	0.123%	1.324%	0.529%
Human carcinogenic toxicity (kg 1,4-DCB)_0	1.510%	64.291%	0.103%	0.802%	0.004%
Human non-carcinogenic toxicity (kg 1,4-DCB)_0	2.793%	63.402%	0.121%	1.470%	0.006%
Land use (m^2a crop eq)_0	7.425%	60.330%	2.913%	2.759%	0.039%
Mineral resource scarcity (kg Cu eq)_0	47.525%	33.422%	1.743%	13.778%	0.047%
Fossil resource scarcity (kg oil eq)_0	1.279%	65.626%	0.542%	0.548%	0.004%
Water consumption (m^3)_0	16.392%	59.793%	0.585%	7.711%	0.016%

Table 4.7 - Scenario A: midpoint characterization results

Impact category	Station	Energy	Transports	Maintenance	Disposal
Global warming (kg CO_2 eq)_A	1.990%	64.306%	0.413%	0.528%	0.005%
Stratospheric ozone depletion (kg CFC11 eq)_A	0.671%	65.313%	0.220%	0.356%	0.003%
Ionizing radiation (kBq Co-60 eq)_A	28.202%	47.622%	5.155%	18.877%	0.145%
Ozone formation, Human healt (kg NOx eq)_A	2.596%	63.014%	2.205%	0.667%	0.005%
Fine particulate matter formation (kg PM2.5 eq)_A	2.690%	63.600%	1.475%	1.206%	0.008%
Ozone formation, Terrestrial	2.641%	63.005%	2.215%	0.698%	0.005%

Impact category	Station	Energy	Transports	Maintenance	Disposal
ecosystems (kg NOx eq)_A					
Terrestrial acidification (kg SO_2 eq)_A	1.869%	63.857%	1.429%	0.742%	0.005%
Freshwater eutrophication (kg P eq)_A	0.523%	65.146%	0.030%	0.292%	0.001%
Marine eutrophication (kg N eq)_A	0.657%	65.173%	0.035%	0.444%	0.002%
Terrestrial ecotoxicity (kg 1,4-DCB)_A	32.968%	39.475%	4.358%	23.134%	0.064%
Freshwater ecotoxicity (kg 1,4-DCB)_A	2.274%	63.398%	0.099%	1.189%	0.612%
Marine ecotoxicity (kg 1,4-DCB)_A	2.463%	63.366%	0.123%	1.324%	0.529%
Human carcinogenic toxicity (kg 1,4-DCB)_A	1.510%	64.291%	0.103%	0.802%	0.002%
Human non-carcinogenic toxicity (kg 1,4-DCB)_A	2.793%	63.402%	0.121%	1.470%	0.006%
Land use (m^2a crop eq)_A	7.425%	60.330%	2.913%	2.759%	0.028%
Mineral resource scarcity (kg Cu eq)_A	47.525%	33.422%	1.743%	13.778%	0.029%
Fossil resource scarcity (kg oil eq)_A	1.279%	65.626%	0.542%	0.548%	0.004%

Impact category	Station	Energy	Transports	Maintenance	Disposal
Water consumption (m^3)_A	16.392%	59.793%	0.585%	7.711%	0.014%

Table 4.8 - Scenario B: midpoint characterization results

Impact category	Station	Energy	Transports	Maintenance	Disposal
Global warming (kg CO_2 eq)_B	1.500%	98.065%	0.408%	0.024%	0.003%
Stratospheric ozone depletion (kg CFC11 eq)_B	0.357%	99.393%	0.217%	0.031%	0.002%
Ionizing radiation (kBq Co-60 eq)_B	10.320%	67.760%	5.077%	0.586%	0.038%
Ozone formation, Human health (kg NOx eq)_B	2.018%	95.740%	2.173%	0.066%	0.003%
Fine particulate matter formation (kg PM2.5 eq)_B	1.737%	96.614%	1.451%	0.195%	0.003%
Ozone formation, Terrestrial ecosystems (kg NOx eq)_B	2.038%	95.706%	2.182%	0.071%	0.003%
Terrestrial acidification (kg SO_2 eq)_B	1.349%	97.070%	1.406%	0.173%	0.002%
Freshwater eutrophication (kg P eq)_B	0.344%	99.537%	0.029%	0.089%	0.000%
Marine eutrophication (kg N eq)_B	0.319%	99.563%	0.034%	0.082%	0.001%
Terrestrial ecotoxicity (kg 1,4-DCB)_A	16.241%	59.989%	4.324%	5.261%	0.007%

Impact category	Station	Energy	Transports	Maintenance	Disposal
Freshwater ecotoxicity (kg 1,4-DCB)_A	1.849%	96.845%	0.098%	0.598%	0.610%
Marine ecotoxicity (kg 1,4-DCB)_A	1.938%	96.786%	0.122%	0.628%	0.527%
Human carcinogenic toxicity (kg 1,4-DCB)_A	1.214%	98.205%	0.102%	0.477%	0.001%
Human non-carcinogenic toxicity (kg 1,4-DCB)_A	2.275%	96.847%	0.119%	0.755%	0.003%
Land use (m^2a crop eq)_B	5.056%	91.772%	2.891%	0.268%	0.013%
Mineral resource scarcity (kg Cu eq)_B	41.732%	50.335%	1.723%	6.197%	0.012%
Fossil resource scarcity (kg oil eq)_B	0.784%	98.641%	0.535%	0.038%	0.001%
Water consumption (m^3)_B	8.883%	90.409%	0.577%	0.124%	0.007%

As anticipated by Endpoint results, “Energy” is the most impacting group for all categories in the three scenarios. However, it should be noted that in the categories “Ionizing radiation”, “Terrestrial ecotoxicity” and “Mineral resource scarcity” a good percentage of impact is also due to other groups in addition to that of “Energy”, as can be seen from the *Figure 4.13* obtained from the data in the tables above. This figure represents Midpoint characterization results related to 100%. Furthermore, only the midpoints “Ionizing radiation” and “Terrestrial ecotoxicity” of scenarios 0 and A are more impactful than Scenario B. This is due to the raw materials necessary for the construction of the photovoltaic panels and other components of the station.

In the following subsections, the midpoints “Ionizing radiation”, “Terrestrial ecotoxicity”, “Land use”, “Mineral resource scarcity” and “Water consumption” found during the evaluation of the comparison will be observed in depth. The other midpoints will not be treated in depth as they are governed by the higher energy demand purchased from the grid due to the lack of photovoltaic panels. Furthermore, the definitions of the different midpoints are described in *Appendix I*.

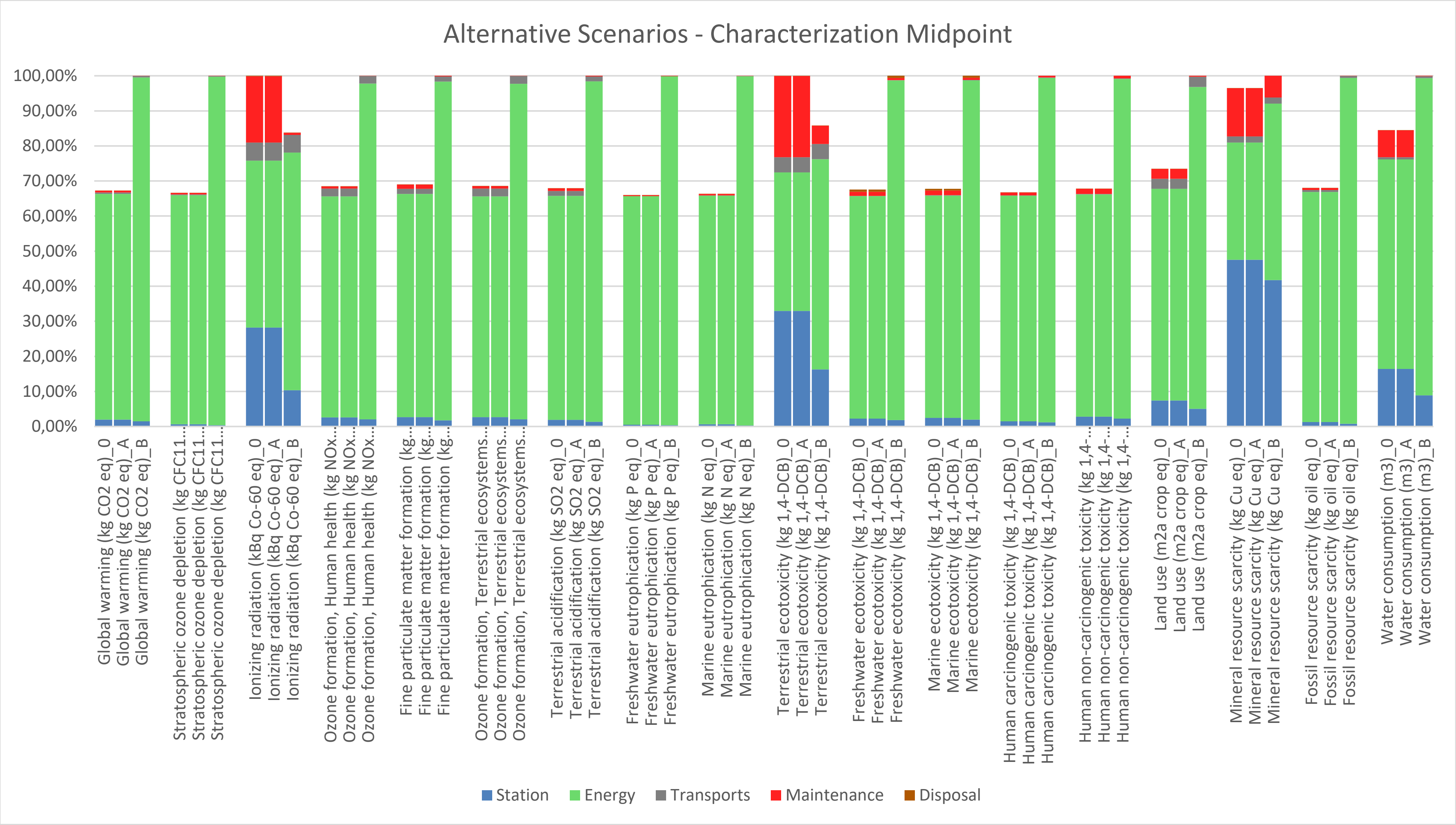

Figure 4.13 - Comparison of the alternative scenarios: midpoint characterization results

In *Figure 4.14* it is possible to observe the normalized results for the three scenarios compared. Normalized results show a predominance in impacts to “Freshwater ecotoxicity”, “Marine ecotoxicity”, “Human carcinogenic toxicity” and “Human non-carcinogenic toxicity”. It is important to note that the “Ionizing radiation” and “Terrestrial ecotoxicity” impact categories mentioned above whose impact was due to the materials needed for the construction of some components of the station actually have a negligible impact once the data are normalized.

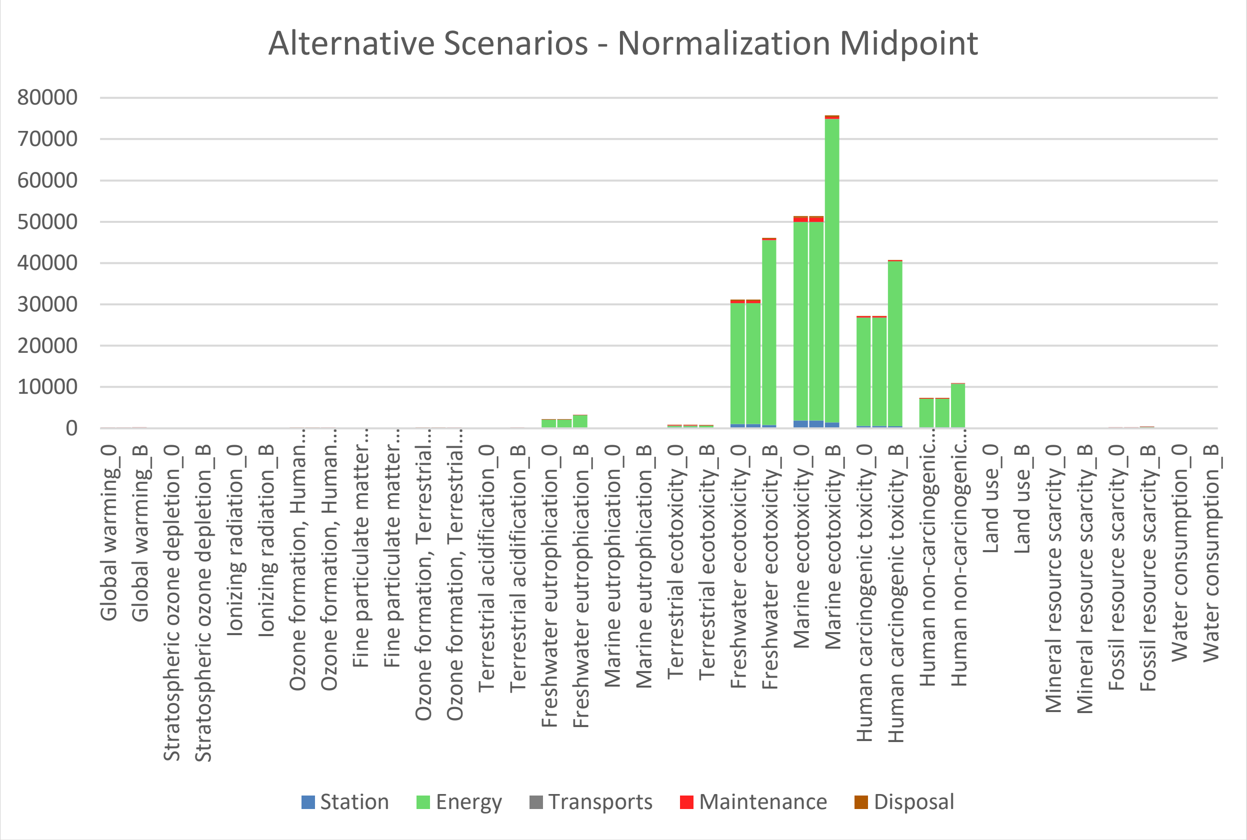

Figure 4.14 - Comparison of the alternative scenarios: midpoint normalization results

Ionizing radiation

The differences in the impacts between Scenario B and scenarios 0 and A (which are similar to each other), are due to the absence of solar panels and batteries in Scenario B. This results into a higher percentage energy value caused by the greater consumption of electricity purchased from the grid in Scenario B (absence of photovoltaic panels). At the same time, due to the absence of these latter components, the impacts for the construction of the station and their disposal are lower than in scenarios 0 and A. This is a result of the type and quantity of minerals extracted for the construction and substitution of mostly solar panels. Additionally, concrete is the most impactful material among those used for the construction of the antenna also due to the large quantity used, as the LCA evaluates all direct and non-direct impacts.

Human toxicity and ecotoxicity

The following midpoints are grouped in this section: terrestrial ecotoxicity, freshwater ecotoxicity, marine ecotoxicity, human carcinogenic toxicity and human non-carcinogenic toxicity.

The terrestrial ecotoxicity midpoint results for scenarios 0 and A are mainly driven by energy consumption (approximately 39% of the value). In addition, the maintenance and the station contribute approximately 23% and 32% to the total impact of this indicator, respectively. Energy has an impact of approximately 60% in Scenario B. Moreover, maintenance and station categories contribute approximately 5% and 16% respectively, to the total impact in the third scenario.

Similarly to what was said for the previous midpoint, the differences between scenarios 0 & A and B are due to the absence of solar panels and batteries in the third scenario. In this case, the causes of the impacts are also due to the type and quantity of minerals extracted for the construction and replacement of solar panels and diesel generators.

The other four midpoint results (freshwater ecotoxicity, marine ecotoxicity, human carcinogenic toxicity and human non-carcinogenic toxicity) are mainly driven by energy consumption for all 3 analysed scenarios. This is due to the large amount of electricity used for the normal operation of the station.

Land use

The land use midpoint results are mainly driven by energy consumption for all 3 analysed scenarios. However, it should be noted that in 0 and A scenarios the station has an impact of about 7%. Otherwise, in B scenario, the station has an impact of 5% due to the absence of solar panels and batteries.

Water use

The water use midpoint results are mainly driven by energy consumption for all 3 scenarios analysed. However, it should be noted that for scenarios 0 and A the station and the maintenance have an impact approximately +8% and +7% respectively, compared to Scenario B due to the absence of solar panels and batteries.

Mineral resource scarcity

In scenarios 0 and A, the midpoint of mineral resource scarcity is the only impact category where energy does not have the highest impact value. Indeed, the station group mainly drives the results. The impact exerted by the station is around 48% (0 and A scenarios) and around 41% in Scenario B. Notwithstanding in the latter scenario the dominance of the impact caused by energy consumption is confirmed, around 50% of the impacts. Due to the absence of solar panels and batteries in Scenario B the impacts on resource consumption are lower when compared to scenarios 0 and A. In any case, in this category all three scenarios have a considerable impact due to the raw materials used for the various components of the New Norcia station. Indeed, in 0 and A scenarios the most impacting elements are concrete, diesel generators, transformers, and solar panels; in B scenario the same, obviously excluding the panels.

4.2 Life Cycle Interpretation

The Single score results analysed with the *ReCiPe* method (2016) are now reported for the three cases examined in the previous chapter. Specifically, a detailed sum up is initially provided for Scenario 0 only. Subsequently the final evaluation of the comparison between the three hypothesized scenarios (0, A and B) is reported.

4.2.1 Life Cycle Interpretation Scenario 0

From the Single score results obtained with the *ReCiPe* method shown in *Figure 4.15*, it is possible to see how the impact caused by Energy is indisputable. It should be remembered that this group includes 1.36 GWh/yr of high voltage electricity purchased from the national grid and 10000 L per year of diesel used to run the backup diesel generators. The total contribution of energy is, indeed, equal to approximately 94% of the total. This is mainly due to the large amount of electricity purchased each year and secondly to the litres of diesel burned per year for energy production, all considering 50 years of the station's life.

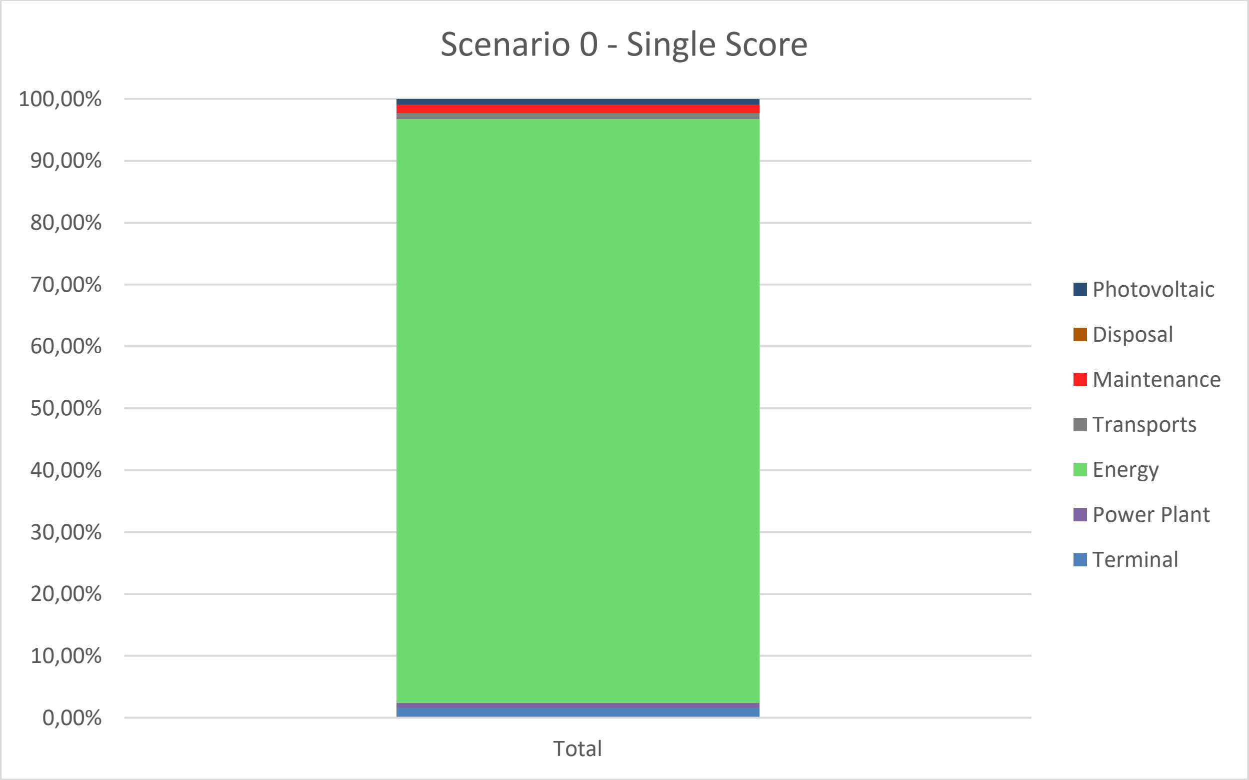

Figure 4.15 - Scenario 0: single score results

The other groups that exceed 1% of the total impacts are the Terminal, Maintenance and Transportation. As emerged in *Figure 4.15* the impacts of the raw materials and components used for the construction of the entire station are negligible compared to Energy. This is due to their reduced impact if considered the entire life cycle of the plant. As for transport, considering the 50 years of life of the station their impact is mostly negligible.

Lastly, photovoltaic Panels and Disposal have a total impact of less than 1%.

4.2.2 Life Cycle Interpretation Scenarios 0, A & B

From the Single score results obtained with the *ReCiPe* method shown in *Table 4.9* and *Figure 4.16*, it is possible to see how the impact caused by Energy is indisputable for all the three scenarios. Please note that the tables below represent the impacts of the three scenarios compared to 100%, therefore only B case (the most impacting case) will have 100% total.

Table 4.9 - Alternative scenarios: total single score results

Total	Station	Energy	Transports	Maintenance	Disposal
Total_0	2.244%	64.016%	0.677%	0.881%	0.007%
Total_A	2.244%	64.016%	0.677%	0.881%	0.006%
Total_B	1.628%	97.487%	0.667%	0.215%	0.003%

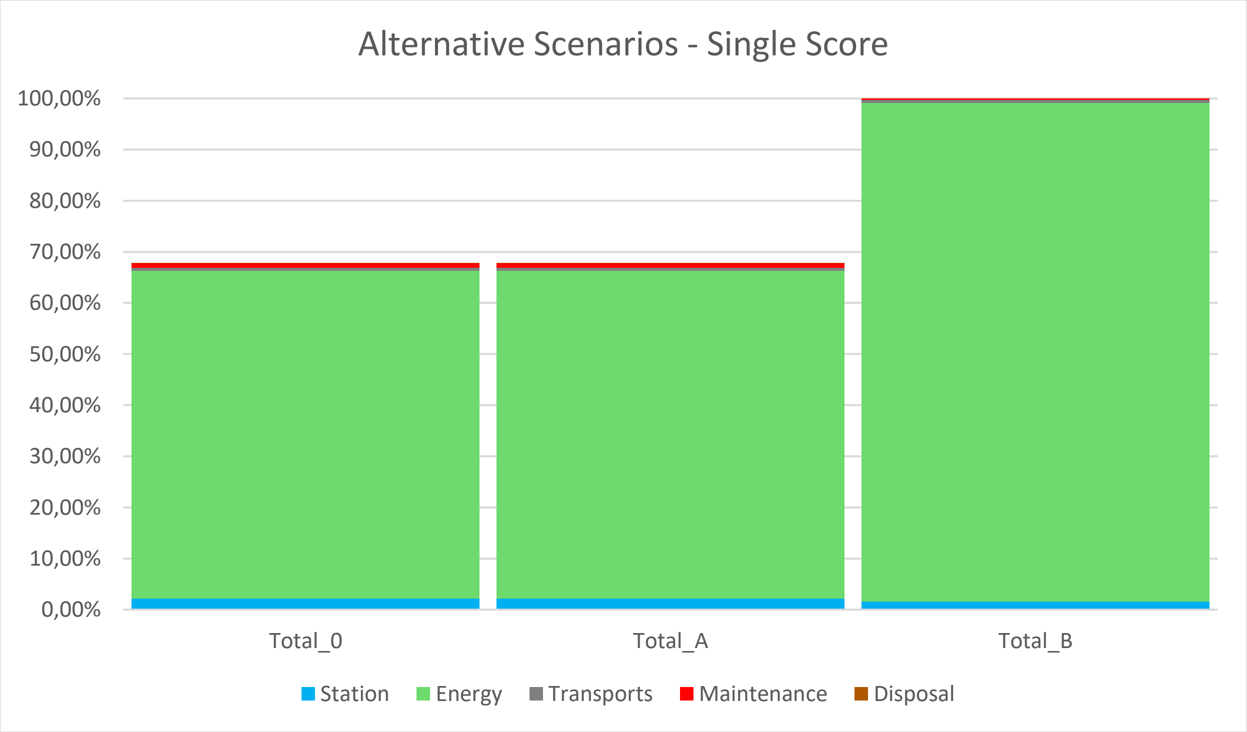

Figure 4.16 - Comparison of the alternative scenarios on the basis of the single score results

According to *Table 4.9* and *Figure 4.16*, the impacts due to the “Energy” group have a value of 64% for scenarios 0 and A and 97% for Scenario B. This great difference (+33%) between scenarios

0 & A and B is due to the absence of photovoltaic panels and batteries in Scenario B. Indeed, being able to produce 470 MWh of electricity on site of the 1360 MWh of total annual consumption thanks to the panels, contributes to reduce the purchase of electricity from the grid by about 35%. This also has direct benefits for the environment since it significantly reduces the purchase of energy that is produced using, for example, fossil sources.

All other differences are always connected to the absence of solar panels and batteries in Scenario B. Indeed, in scenarios 0 & A the Station affects +0.61% as compared to Scenario B where the station affects 1.63%. In scenarios 0&A, Maintenance affects +0.67% as compared to Scenario B where the maintenance affects 0.21%. The reduced impacts of these groups in Scenario B are obviously due to the absence of components installed and which require maintenance during the life cycle of the station. Clearly, Scenario B is not the scenario of the case study, but it allows highlighting the importance of solar panels and the usefulness of producing electricity on site using renewable energy sources. Transport does not show appreciable differences, settling on an impact value of approximately 0.68% for all three scenarios.

Finally, the Disposal group has an impact of approximately 0.01% for all three scenarios. However, the interesting feature to highlight concerns especially scenarios 0 and A, since the main differences in the Disposal group between Scenario 0 and Scenario A concern solar panels disposal. In Scenario 0, an end of life considers that 90% of the materials comprising the solar panels are recycled and the remaining 10% is sent to landfill. To realize this scenario, the European “Full Recovery End of Life Photovoltaic (FRELP)” LIFE project was used as a reference (Latunussa et al., 2016). The FRELP project focuses on the development of an innovative process based on a series of mechanical and chemical treatments to recycle or recover waste crystalline-silicon (C-Si) photovoltaic (PV) panels (Latunussa et al., 2016). Whereas in Scenario A, 100% of the solar panels are recycled. Consequently, the impacts of Scenario A, which is completely the same as Scenario 0 except for the Disposal scenario, has a slightly lower total impact than Scenario 0.

CONCLUSIONS

This thesis allowed understanding how sustainability and sustainable development are becoming important reference points for space agencies. Indeed, in this dissertation, a screening LCA study is proposed with the aim of evaluating the environmental impacts of the satellite tracking ground station located in New Norcia (AU) that can be used as a benchmark for similar future constructions. The assessment showed that among all the components of the station, the consumption of electricity from the electricity grid causes more than 90% of the environmental impacts overall. To confirm the data obtained by the case study (Scenario 0) two further scenarios were created. Firstly, Scenario A, which differs from the case study (Scenario 0) in the disposal of solar panels that are all recycled. Then, Scenario B, which is identical to Scenario 0 but does not include photovoltaic panels and batteries. As the differences between Scenario 0 and Scenario A are masked by the impact caused by electricity, the results obtained from the comparison between Scenario 0 and Scenario B were much more interesting. The comparison showed that the energy produced by solar panels is able to reduce environmental impacts by more than 30%. Indeed, the efficiency of the solar panels installed in 2017 made it possible to significantly reduce the impact of energy consumption. Considering the potential impacts caused by the materials required for their construction, solar panels play a key role in reducing the overall impacts of the New Norcia site. Therefore, on-site energy production is the optimal solution to reduce the impacts caused by energy consumption. To confirm this, it was possible to see how in the normalized graph reported in *Figure 4.14*, the Scenario 0 with solar panels is more advantageous in terms of impacts for each midpoint. Furthermore, as can be seen from the graph reported in *Figure 4.10* related to Scenario 0, the most relevant impacts evaluated through the normalized midpoints are always caused by Energy. This is because about 70% of the energy purchased by the grid from the New Norcia station comes from non-renewable sources such as coal (International Energy Agency, 2021). Indeed, the Australian government's energy mix is mainly based on fossil fuels. Consequently, the impacts caused by Energy can be considered as indirect since ESA is not directly responsible for them. The use of the panels is therefore indisputable. Furthermore, although the production of the panels causes impacts in some impact categories due to the materials used, it should be remembered that in this analysis all the impacts were spread over the 50-year life of the station. Indeed, when compared to the impacts caused by Energy, those of solar panels are minimal. This is another peculiarity in favour of their use. Lastly, all the other components have negligible impacts considering the station's 50 years of life.

Future improvements for the research

One of the most immediate and concrete solutions to decrease the impacts related to the use of energy involves the installation of additional photovoltaic panels to produce more “sustainable” electricity on site. This will make it possible to reduce the purchase from the electricity grid. In this way, the impacts will be considerably reduced given that the Australian energy mix is mostly oriented on the production of electricity using fossil sources. The only problem with solar panels is related to critical raw materials (CRMs). CRMs are those commodities that are economically and strategically important for the European economy but have a high risk associated with their supply (Ferro & Bonollo, 2019). To meet future energy demand through renewable energies, the demand for solar panels and other renewable energies will increase. As a result, the consumption of raw materials needed to manufacture these technologies is expected to dramatically increase over the coming decades (Alves Dias et al., 2020). For these reasons, the most immediate solution to reduce the environmental impacts due to the construction of new solar panels and to reduce the costs of their purchase is to recycle their components when possible.

ESA also plans to improve the energy efficiency of the panels. About 20% of electricity is put back into the electricity grid because there are no batteries connected to the panels for energy storage. Therefore, in order not to waste energy, it is possible to evaluate the purchase of new performing batteries such as hydrogen fuel cells. Finally, the purchase of wind sails is planned to produce energy thanks to the intensity of the wind currents at high altitudes.

The possibility of comparing the Australian energy mix with that of the more virtuous countries in the production and use of energy will also be evaluated through a further in-depth study. In this way it will be possible to have a clearer idea about the causes of the impacts related to the different energy mixes of different countries.

Lastly, to reduce the negative effects of transport on the environment, despite its reduced impact when considering the station's 50 years of life, transport carriers could be shifted from roads to railways if these are present. A final consideration may be to purchase raw materials in places closer to the site to be built.

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Appendix I

This appendix briefly reports the official descriptions of the PRé Consultants of the individual midpoints.

Global warming

The characterization factor of climate change is the global warming potential, based on IPCC 2013 report. The unit is yr/kg CO_2 equivalents (PRé Consultants, 2021).

Ozone depletion

The characterization factor for ozone layer depletion accounts for the destruction of the stratospheric ozone layer by anthropogenic emissions of ozone depleting substances (ODS). The unit is yr/kg CFC-11 equivalents (PRé Consultants, 2021).

Ionizing radiation

The characterization factor of ionizing radiation accounts for the level of exposure for the global population. The unit is yr/kBq Cobalt-60 equivalents to air (PRé Consultants, 2021).

Fine particulate matter formation

The characterization factor of fine particulate matter formation is the intake fraction of PM2.5. The unit is yr/kg PM2.5 equivalents (PRé Consultants, 2021).

Photochemical ozone formation, terrestrial ecosystems

The characterization factor is determined from the change in intake rate of ozone due to change in emission of precursors (NOx and NMVOC). The unit of ecosystem ozone formation potential is yr/kg NOx equivalents (PRé Consultants, 2021).

Photochemical ozone formation, human health

The characterization factor is determined from the change in intake rate of ozone due to change in emission of precursors (NOx and NMVOC). The unit of human health ozone formation potential is yr/kg NOx equivalents (PRé Consultants, 2021).

Terrestrial acidification

The characterization factor for terrestrial acidification is Acidification Potential (AP) derived using the emission weighted world average fate factor of SO_2. The unit is yr/kg SO_2 equivalents (PRé Consultants, 2021).

Freshwater eutrophication

The characterization factor of freshwater eutrophication accounts for the environmental persistence (fate) of the emission of P containing nutrients. The unit is yr/kg P to freshwater equivalents (PRé Consultants, 2021).

Marine eutrophication

The characterization factor of marine eutrophication accounts for the environmental persistence (fate) of the emission of N containing nutrients. The unit is yr/kg N to marine equivalents (PRé Consultants, 2021).

Human toxicity and ecotoxicity

The characterization factor of human toxicity and ecotoxicity accounts for the environmental persistence (fate) and accumulation in the human food chain (exposure), and toxicity (effect) of a chemical. The unit is yr/kg 1,4-dichlorobenzeen (1,4-DCB) emitted (PRé Consultants, 2021).

Land use

The characterization factor of Land use is the amount of land transformed or occupied for a certain time. The unit is m^2*yr (PRé Consultants, 2021).

Water use

The factor for the water use is the amount of freshwater consumption. The unit is m^3 water consumed. Current implementation includes regionalized characterization factors in the endpoint version of the method (PRé Consultants, 2021).

Mineral resource scarcity

The characterization factor for mineral resource scarcity is the surplus ore potential. The unit is kg Copper (Cu) equivalents (PRé Consultants, 2021).

Fossil resource scarcity

The characterization factor of fossil resource scarcity is the fossil fuel potential, based on the higher heating value. The unit is kg oil equivalents (PRé Consultants, 2021).

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